Transitioning the Discrete Manufacturing Industry from a Linear to a Circular Economy

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TRANSITIONING THE DISCRETE MANUFACTURING INDUSTRY FROM A LINEAR TO A CIRCULAR ECONOMY

BY
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AALBORG UNIVERSITY
DENMARK

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CV

Markus Thomas Bockholt was born on the 20th of December 1990 in Wiesbaden, Germany. After a moderately successful time at school, he did his civilian service as a nurse at St. Vincent's, Aulhausen; an institution that supports people with disabilities. The hard work during his service supported him in his decision to study and thus delay his entry into the working life for a couple of years. He began to study Environmental Engineering at the University of Applied Sciences RheinMain which he completed with great success in 2014. An Erasmus term in Portsmouth ignited his love for the United Kingdom. He therefore decided to pursue a Master in Innovation Management at the University of Strathclyde, Glasgow. Within the framework of the Erasmus program, Markus moved to Denmark to complete his studies at Aalborg University in 2016. He eventually decided to combine his passion for environmental engineering and innovation management to do an industrial PhD in the field of circular economy.

ENGLISH SUMMARY

Our current economic system is fundamentally ill-structured. Its linear layout, which works under the take-make-waste premise, ignores the natural limits of planet earth, which makes its failure in the long run inevitable. 250 years after the first industrial revolution, human society sees itself confronted with consequences such as environmental pollution, global warming and critical resource depletion. There is academic and political consensus that a transformation to a sustainable, circular economy is an imperative. Circular Economy is a sustainable development initiative, aiming to eliminate the negative impact of human production and consumption on the environment. It aims at keeping raw materials, components and products in a cycle, following the example of nature. This is achieved by changing from linear material and energy flows to materials cycles and renewable and cascade-type energy flows.

First supranational laws have been passed that make discrete manufacturing companies responsible for the products they produce, and ultimately take responsibility for the point at which they reach the EoL (End-of-Life) stage and turn into waste. Over the past decades, the discrete manufacturing industry has produced and sold millions of goods to the consumer market. However, this has happened under the traditional take-make-waste paradigm without considering multiple product life cycles.

On the one hand, the conventional, transaction-based business model used here makes it very difficult to locate products at the end of their life cycle and, on the other hand, the absence of life cycle-based product design makes it very difficult to recover sufficient value. This makes EoL products a legacy problem for many producers, since economic exploitation is an unsolved problem. In contrast to the traditional forward supply chain, in which today's research and industry have great expertise, reverse supply chains, their functions and mechanisms are largely unexplored, especially with regard to EoL products.

The present thesis supports the discrete manufacturing industry in the current brown-field transition through its objective:

To understand transitional challenges and to develop reverse supply chain capabilities for closing resource loops in the discrete manufacturing industry

The insights gained in this thesis cover the most important basics needed to build a financially and environmentally sound reverse supply chain in the current transitional phase we are in. The special focus is on the short- midterm transitional phase targeting the prevalent legacy problem.

- Factors impacting the financial profitability of current EoL take-back initiative
- Supply chain strategies for the search of EoL products
- Supply chain strategies for the recovery of value from EoL products
- Maximization of resource effectiveness through utilizing product data

The solutions presented include structural supply chain elements, such as factors to be considered when designing reverse supply chains as well as supply chain strategies for the search and recovery of EoL product value. This dissertation contributes to literature in twofold ways. Firstly, contributing to existing literature on reverse supply chains with design element especially relevant for returning EoL products. Secondly, as a pioneer in classifying search and value recovery strategies enabling a structured transition in the current brownfield scenario.

DANSK RESUME

Det nuværende økonomiske system er grundlæggende dårligt struktureret, da det lineære flow fungerer under ved udvinding af ressourcer, produktion og brug af produkter efterfulgt af bortskaffelse af produkter. Dette ignorerer planetens naturlige grænser og gør dens nederlag i det lange løb uundgåelig. 250 år efter den første industrielle revolution ser det menneskelige samfund sig konfronteret med konsekvenser såsom miljøforurening, global opvarmning og kritisk ressourceudtømning. Der er akademisk og politisk enighed om, at en transformation til en bæredygtig, cirkulær økonomi er et essentielt. Cirkulær økonomi er et bæredygtigt udviklingsinitiativ, der sigter mod at eliminere den negative indvirkning af produktion og forbrug på miljøet, der sigter mod at holde råvarer, komponenter og produkter i omløb, som følger naturens kredsløb. Dette opnås ved at skifte fra et lineært flow af materialer og energistrømme til materialecyklusser og vedvarende energistrømme.

De første overstatslige love er vedtaget, der gør de diskrete fremstillingsvirksomheder ansvarlige for de produkter, de producerer, og tager ansvaret for det punkt hvor de når EoL (End-of-Life) -stadiet og forvandles til skrot. I løbet af de sidste årtier har den diskrete fremstillingsindustri produceret og solgt millioner af varer til forbrugermarkedet. Dette er imidlertid sket under det traditionelle produktions paradigme uden at overveje produktlivscyklusser.

På den ene side gør den konventionelle, transaktionsbaserede forretningsmodel det meget vanskeligt at lokalisere produkter i slutningen af deres livscyklus, og på den anden side gør fraværet af livscyklusbaseret produktdesign det meget vanskeligt at indkassere tilstrækkelig værdi. Dette gør EoL-produkter til et nedarvet problem for mange producenter, hvor økonomisk udnyttelse er et uløst problem. I modsætning til den traditionelle produktion, som nutidens har forskning og industri har stor ekspertise indenfor, så er den tilbageløbende forsyningskædes funktioner og mekanismer stort set uudforskede, især med hensyn til EoL-produkter.

Denne afhandling understøtter den diskrete fremstillingsindustri i dens evolution imod cirkulære fremstillingsprocesser gennem dens mål:

At forstå udfordringer og udvikle tilbageløbende forsyningskæde evner til at danne ressourcecyklusser i den diskrete produktions industri.

Den indsigt der er opnået i denne afhandling, dækker de vigtigste grundlæggende behov for at opbygge en økonomisk og miljømæssigt forsvarlig tilbageløbende forsyningskæde i den aktuelle overgangsfase som vi befinder os i. Fokusset er på den korte og mellemlange overgangsfase, der er rettet mod det fremherskende arvs problem. Så som:

- Faktorer, der påvirker den økonomiske rentabilitet af det nuværende EoL-tilbagetagelsesinitiativ
- Forsyningskæde strategier til søgning efter EoL-produkter
- Forsyningskæde strategier for nyttiggørelse af værdi fra EoL-produkter
- Maksimering af ressourceeffektivitet gennem anvendelse af produktdata

De præsenterede løsninger inkluderer strukturelle forsyningskædelementer, såsom faktorer, der skal overvejes ved design af tilbageløbende forsyningskæder samt forsyningskæde-strategier til søgning og nyttiggørelse af EoL-produktværdi. Denne afhandling bidrager til litteraturen på to måder. Først ved at bidrage til eksisterende litteratur om tilbageløbende forsyningskæder, der især er relevant for returnering af EoL-produkter. For det andet, som en pioner inden for klassificering af søge- og værdigenvindingsstrategier, der muliggør en struktureret overgang for den nuværende fremstillingsproduktion.

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Sir Isaac Newton once said he had seen farther by standing on the shoulders of giants. Whoever works in research knows this famous quotation, which means: "Using the understanding gained by major thinkers who have gone before in order to make intellectual progress ". Apart from this interpretation, I am convinced that any research talent can only develop its abilities if it stands on the shoulders of a stable and supportive social environment. This includes family, friends and colleagues. I am aware that I am privileged to be born into such an environment and therefore I would like to thank the most important people in the following.

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CHAPTER 1. INTRODUCTION

Our planet Earth stood in a biological balance for hundreds of millions of years before the evolution of humanity. Mother Nature nourished its inhabitants abundantly and generously. At that time, the concept of waste did not exist. Nature worked in a system of nutrients and metabolism that represented a natural cycle. Macronutrients, consisting of carbon, hydrogen, oxygen, and hydrogen, circulated in an endless cycle (McDnough and Braungart, 2010). Michael Braungart vividly illustrates the circular functions of his nature using the example of a cherry tree. The tree produces thousands of cherry blossoms in the spring, but only a tiny part of these blossoms finally develop into cherries. Most of the flowers fall off the tree after the blossoming period and land on the earth, where they slowly decompose. There, they nourish various microorganisms that enrich the topsoil of the tree with nutrients and thus support the cherry tree and other plants in their growth and the development of new blossoms (Braungart, 2007).

From the onset of the first industrial revolution, humanity has set this natural balance out of place. Industrial treatment and accumulation of naturally occurring substances have altered the equilibrium of materials on earth. Industrially modified materials cannot any longer be safely returned into the biological cycle.Therefore, a linear supply chain based on the source-make-waste principle has developed in the industrialized world. Contrary to mother nature, this system is not regenerative by design. Considering the natural limits of the earth (limited space, limited resources), it is set-up to fail. A linear system is ill-structured and only valid temporarily. Now, after following the linear system for over 250 years, the initial system flaws catch up with us. On the one hand, a large number of vital raw materials that play an important role in his world today are close to depletion, and on the other hand, we experience critical environmental pollution—finally resulting in a loss of biodiversity and soil, water and air pollution (Rockström et al., 2009; Jackson, 2009; Meadows et al., 2004; WWF, 2014).

A circular economy is a sustainable development initiative, aiming to eliminate the negative impact of human production and consumption on the environment, that aims at keeping raw materials, components and products in a cycle, following the example of nature (EMF, 2013a). This is achieved by changing from linear material and energy flows to materials cycles and renewable and cascade-type energy flows. A circular economy promotes high-value material cycles, but also more traditional cycles like recycling (Korhonen et al., 2018), albeit high-value material is critical for a circular economy to reach its full economic potential (Ghisellini et al., 2016). The concept of the circular economy is implemented in three different levels (Yuan et al., 2006). These are: (i) micro-, (ii) meso, and (iii) macro-level. The micro-level deals with the individual industrial firm. The meso-level deals with the development of an eco-industrial network that brings benefits to local production systems and the local environment (Yuan et al., 2006). The macro-level deals with a circular economy in cities, provinces, and regions (Ghisellini et al., 2016). In the context of my Ph.D. thesis, I am dealing with the micro-level, more precisely with processes that firms use to operationalize a circular economy, as this is still mostly unclear (Urbinati et al., 2017). Furthermore, it is vital to distinguish if a circular economy is to be found in the process industry or in the discrete manufacturing industry. The process industry can be characterized by processes like mixing, blending, extrusion, chemical reactions, baking, and annealing (Prosman, 2018). The process industry involves a continuous mass flow of raw materials and end products. Finished products can often not re-enter the production stage once finished (French and La-forge, 2006). The discrete manufacturing industry transforms raw materials into products through product design and manufacturing operations. These products usually consist of at least two components, but most of them include many. Just like the end product, each component has specific raw material value. This describes the market price of the raw materials that the component contains.

On the other hand, each product and each component have a functional value. The functional value describes the value added to the raw materials by the design and manufacturing process (Kumar, 2007). Typically the financial and environmental potential of recovering the functional value is a multitude of recovering the raw material value (Stahel, 2010, EMF, 2013a).

Apart from the negative consequences that can be countered by the establishment of a circular economy, it also offers companies the chance to gain a significant competitive advantage. Calculations by FIFC (Finland's Independence Celebration Fund) and the business consultancy McKinsey have shown that the global transition to a Circular Economy can generate over a billion dollars in additional revenue (FICF and Mckinsey, 2014). Successful examples of the implementation of the Circular Economy are Elon Musk's Space Ex or Apple. SpaceX rocket missions blasted into the atmosphere, reusing a refurbished rocket launcher, a move that cut an estimated 30 percent off its blast-off costs (Gradi, 2017). By applying circularity in its approach, SpaceX was able to drive the US National Aeronautics and Space Administration (NASA) out of the market, which have now partnered up with SpaceX for coming space expeditions (NASA, 2020). Apple is now scaling up an extensive take-back program for used products, currently mainly recycling their most sensitive materials such as cobalt, aluminum, tin, and copper. By developing a highly efficient disassembly robot, which is able to disassemble 15 types of iPhones at a rate of 200 per hour, their operations already contribute to a positive business case. Currently, Apple aims to move from recycling to remanufacturing or repair to unlock the full potential of the circular economy (Phips, 2019).

The environmental and economic advantages and potentials of the Circular Economy have not gone unnoticed among national and supranational legislators. On a national level, Germany was a first mover in the mid-1990s with the enactment of the Closed Substance Cycle and Waste Management Act (Su et al., 2013). The second country in line was Japan, which implemented the Basic law for establishing a re-cycling-based society in 2000 (METI, 2004). In 2008, China followed as a significant power with the "Circular promotion law of the People's Republic of China" (Lieder and Rashid, 2016). On a supranational level, the 2015 Circular Economy Strategy, which was adopted by the EU, is the first step in strengthening the international cooperation of all EU states with the common goal of a circular economy. In the European context, a first concrete directive that has a direct impact on manufacturers is the WEEE directive. The WEEE Directive 2012/19/EU (Waste of Electrical and Electronic Equipment) aims at the prevention of waste electrical and electronic equipment and the reduction of such waste through reuse, recycling, and other forms of recovery. The directive holds producers responsible for their products, even after leaving the producer's ownership. It sets minimum standards for the treatment of waste electrical and electronic equipment in the EU in order to contribute to sustainable development in the long term. At this stage, the directive only covers specific product categories, but a general extension is expected (Gallo et al., 2011).

Existing and forthcoming legislative pressure constitutes a driver for significant industrial change. Prolonged producers responsibility and circular economy shift from a nice-to-have, which in most cases if at all exists as a small-scale CSR initiative, to an essential part of the core business for manufacturers (De Anglis et al., 2018) This legislative urgency does not make research in circular business models and circular product design any less critical, but also calls for more short and medium-term solutions.

When considering that many discrete manufacturing products, such as Grundfos' pumps, have a life span of more than ten years, it becomes clear that the manufacturing industry is facing a legacy problem. Millions of products have been produced in the last decades that are neither accessible to the manufacturers through a circular business model nor have been subject to circular design principles, such as design for disassembly, design for remanufacturing, or design for reuse. For these products which are already localized and operating in the market, no design changes can be retrospectively implemented. Therefore it is important to distinguish between “greenfield” and “brownfield” research. Greenfield describes entirely new projects in which, e.g., business models and product design can be altered according to project needs. Brownfield describes the expansions of already existing projects, which makes them subject to certain fixed variables (Belaud et al., 2019). A context-specific example for this could be products which have been sold in the last decades, which are hard to locate due to being sold through a linear, transaction-based business model and at the same time have not been designed for multiple lifecycles.

1.1. THESIS OBJECTIVE

A selected number of first moving manufacturers who understand that circular economy is not a question of if, but rather a question of when, are currently at the beginning of a transitioning phase. The objective of this thesis is to understand transitional challenges and to develop reverse supply chain capabilities for closing resource loops in the discrete manufacturing industry. The thesis contributes to the current transitional, brownfield state but also provides inputs into the greenfield, e.g., new product development.

1.2. STRUCTURE OF THE THESIS

The thesis, as such, forms a covering essay of the published research papers and additional reflections on them. It is divided into five chapters. As figure 1-1 shows, it starts with the introduction which describes the research context, the research need and the thesis objective. The second chapter is the theoretical foundation, which gives an introduction to the main literature representing the theoretical foundation of the thesis. The third chapter is the research design, which presents the research methodologies as well as the underlying rationale for choosing them. The fourth chapter presents the core of the thesis. It is divided into three work packages, each of which contains the specific

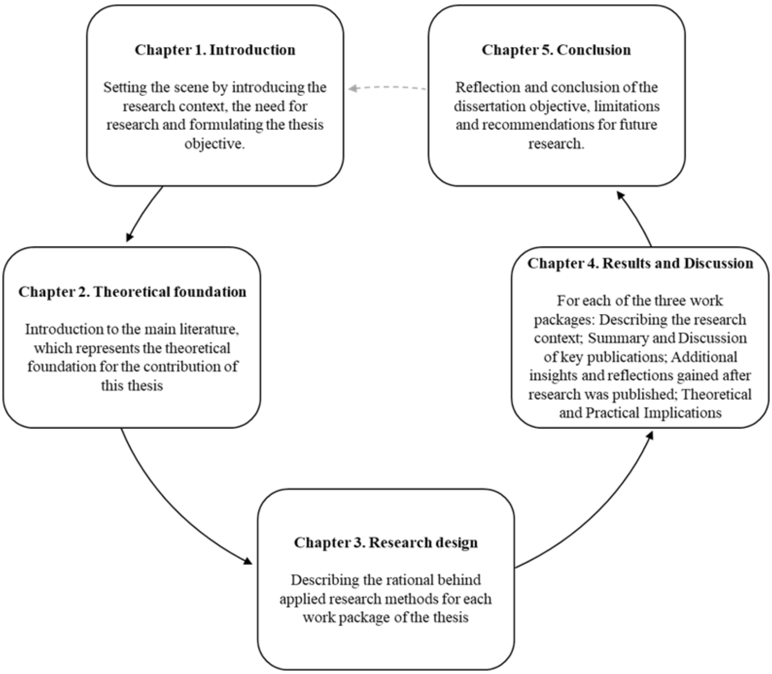

Figure 1-1 Thesis structure

research context, a summary, and discussion of key publications, additional insights and reflections (post-publication), and theoretical as well as practical implications. The fifth and last chapter of this thesis is the conclusion. It reflects and concludes upon the initial research objective and limitations of the research. Additionally, it gives recommendations for future research.

CHAPTER 2. THEORETICAL FOUNDATION

2.1. CIRCULAR ECONOMY

In order to set the theoretical foundation of the circular economy in this thesis, the author asks his readers to read the chapter "introduction" in his publication "Exploring factors affecting the financial performance of End-of-Life take-back program in a discrete manufacturing context". This chapter gives a chronological introduction to the emergence of the circular economy and describes its key concepts (Bockholt et al., 2020).

2.2. SUPPLY CHAIN MANAGEMENT FOR LINEAR SUPPLY CHAINS

The concept of supply chain and its management was first developed and applied in the early '80s (Squire, 2006). Originally, it was used exclusively as a purchasing and logistics concept. Today, the best-known definition of supply chains is from Christopher (1998 p 25): "the management of upstream and downstream relationships with suppliers and customers to deliver superior customer value at less cost to the supply chain as a whole." In the 80s and 90s, the main focus of supply chain management was to describe and, if possible, optimize costs and material flow upstream and downstream of different business entities. The supply chain approach was exclusively linear and related to input and output. In the following years, supply chain management became more strongly associated with operations. In this context, the focus changed to the performance control of material and information flow between the different supply chain partners (Cooper et al., 1997; Hines et al. 2000; Defee and Stank 2005; Hult et al., 2007). Driven by the progressive globalization of manufacturing in the 90s, the goal was to better understand and manage global sourcing. The original focus of purchasing and logistics has broadened to a consideration of the full value chain from raw material extraction, through production, to the end customer. A large part of the existing research is related to the manufacturing industry (Hochrein, 2015). The starting point in supply chain management is always the company to which the study refers, considering upstream and downstream supply chain partners.

In the early 2000s, a new era of supply chain management began with the development and application of lean principles (Womack and Jones 2003; Hines et al., 2004). The application of lean principles increased the focus on efficiency by eliminating waste in the form of, e.g., inventory, waiting time, and unnecessary movement. Numerous authors have extensively researched and confirmed the efficiency benefits of lean (e.g., Womack and Jones 1994, 1996, 2003). The concept of core-efficiency has a financial focus. . It deals with maximizing the intended results of the supply chain, while negative side effects (e.g. costs).. There is a clear link between lean and sustainability. A number of researchers have shown that the efficiency paradigm of 'doing more with less' reduces both the depletion of natural resources and the emission of industrial emissions, thereby protecting the environment (King and Lenoz, 2001; Simpson and Power 2005; Bell et al. 2010). Environmental efficiency is referred to as eco-efficiency, where benefits of doing more with less can lead to reductions in unwanted side-effects, such as minimizing C02 emissions while maintaining production output (Cor-reia et al. 2013). Eco-efficiency is defined by the World Business Council for Sustainable Development as 'being achieved by the delivery of competitively priced goods and services that satisfy human needs and bring the quality of life, while progressively reducing ecological impacts and resource intensity throughout the life cycle to a level at least in line with the earth's carrying capacity' (Braungart et al., 2007). Whereas the Wuppertal Institute defines eco-efficiency as a "social action strategy" seeking to "reduce the use of materials in the economy in order to reduce undesirable environmental impacts and produce a relatively higher degree of economic affluence which is more fairly distributed" (Schütz and Welfens, 2000). Whether core efficiency or eco-efficiency, both concepts can be understood as: "to get more from less: more product or service value with less waste, less resource use or less toxicity" (Braungart et al., 2007 p. 1338). To realize this, eco-efficiency includes various concepts such as de-materialization, increased resource productivity, reduced toxicity, increased recyclability, and extended product lifespan. Each of these strategies has its starting point in the assumption that the supply chain is linear. They accept our earth as a system of production and consumption that irrevocably turns raw materials into waste (Braungart et al., 2007).With supply chain linearity as an underlying mindset, strategies that increase the recyclability of materials, or the extension of product life span try to extend the time a product takes to reach waste status. In reality, however, most materials cannot be recycled properly and are merely down-cycled. This means that the recycling process significantly reduces the quality of the material and the materials cannot be used for their original purpose (e.g., In the so-called bottle-to-bottle cycle, used PET bottles are turned into new PET bottles, but only a small proportion of the old plastic bottle is used for the recycled plastic bottle (Scheel and Vazquez, 2011; Scheel and Vasquez, 2013). The rest is turned into inferior granulate from which, among other things, toys are made in China.). The life cycle of the materials can often be extended, but the status as a resource cannot be maintained in the long run. This is why there such downcycling supply chains can still be considered as linear (Braungart et al., 2007). By continuously minimizing emissions through resource efficiency, the environment can be relieved, but the total eradication of emissions is not possible (Pirker et al., 2002). Eco-efficiency is based on the assumption that industry per se is bad and has a negative relationship with the environment. The concept aims at minimizing this negative influence to reduce the damage. It does reduce the negative impact of industry on nature but does not include a long-term vision of how this negative relationship could be changed to a positive one. As with all other efficiency improvements, eco-efficiency can be seen to reduce the impact per unit of a process, but can also lead to a rebound-effect, that increases the absolute quantity of units.This, in turn, would amortize the positive impact and perhaps even turns it into a negative one. One example of this can be found in global metallurgical aluminum production. The process of energy per metric ton was reduced by 10% in the period 1991-2000 through eco-efficiency improvements. In parallel, the global production of metallurgical aluminum increased by 40% over the same period, resulting in a total increase in energy consumption. Rebound effects caused by efficiency improvements can be found in many industrial examples (Braungart et al., 2007).

Concluding one can say, that after 40 years of extensive research in the field of supply chain management, a well-developed body of literature exists, which deals with core and eco-efficiency improvements (De Anglis et al., 2018). In other words we understand traditional supply chain management its dynamics and actions quite well. In many cases, the required knowledge has already been developed, and shortcomings in the industry are instead due to lack of application than lack of knowledge (Correia et al. 2013). Improving core and Eco-efficiency is a rather incremental approach (Womack and Jones 1994, 1996).

2.3. SUPPLY CHAIN MANAGEMENT FOR REVERSE SUPPLY CHAINS

Reverse supply chains also referred to as closed-loop supply chains, green supply chains, sustainable supply chains, or reverse logistics in contemporary literature (Batista et al., 2018; Farooque et al., 2019). This ambiguity in terminology is a reliable indicator that the field of research is still relatively immature compared to linear supply chains (De Anglis et al., 2018). In the following, the author uses the terminology reverse supply chain. The origin of today's integration of reverse supply chain management into the supply chain management literature comes from the early research interest of the product recovery and remanufacturing literature (Thierry et al. 1995; Fleischmann et al. 1997; Jayaraman et al., 1999; Guide and Van Wassenhove 2009; Loomba and Nakashima 2012). Reverse supply chain management is a dimension of sustainable supply chain management (De Anglis et al., 2018).

In contrast to eco-efficient linear supply chain management, the focus is not only on damage limitation, but is oriented towards value creation (Krikke et al., 2013; Braungart et al., 2007). Reverse supply chains traditionally consist of five core elements. These are „*product acquisition reverse logistics, inspection, and disposition and recovery operations*“ (Guide and Van Wassenhove, 2002). Reverse supply chains must meet indicators in linear supply chain activity performance (e.g., core efficiency and eco-efficiency), but also specific reverse supply chain activities such as the return process, product re-pair/refurbishment, testing, and sorting and remarketing (Guide et al., 2003). As in the traditional linear supply chain, the minimization of costs and negative environmental impacts depends mainly on core / eco-efficiency. However, there is another dimension in reverse supply chain management that is of equal, if not greater importance, eco-effectiveness. Whereby as described above, efficiency approaches focus on minimizing negative factors on the balance sheet, effectiveness approaches describe everything essentially on the positive side of the balance sheet, so to say; how much value can be recovered (Braungart et al., 2007).

In contrast to the above-mentioned efficiency strategies, which aim to prevent negative side effects of production, resource effectiveness strives to maintain the quality and productivity of resources throughout many lifecycles. Hereby, it does not assume that material flow is necessarily linear and that all materials will sooner or later become waste. Resource effectiveness describes the degree to which remaining product value can be recovered.

To understand the concept of resource effectiveness, it is essential to understand the concept of product value as defined by Kumar et al., 2007. Kumar divides product value into two categories. The first is material value, which describes the raw material value that the physical mass of the product carries. The second is functional value, which describes the value that the product and its components have received through the design and manufacturing process (Kumar et al., 2007). Each resource loop in the circular economy recovers a certain composition of material value and functional value. For a detailed explanation and examples the author of this thesis asks his readers to refer to his publication "Exploring factors affecting the financial performance of End-of-Life take-back programs in a discrete manufacturing context" (Bockholt et al., 2020).

Although reverse supply chains have been in operation since the 1920s (e.g., automotive) (De Anglis et al., 2018), the body of literature on reverse supply chain management is less pronounced (Batista et al., 2018; Farooque et al., 2019). There are well-founded, dedicated research papers, but these are often in the area of commercial returns (e.g., Blackburn, 2004). Compared to end-of-life products, the number of uncertainties is significantly reduced, as financial returns are typically new products that have been broken during the warranty period.

On the other hand, commercial returns are only a side business in addition to the core business. Reverse supply chains are typically treated as a silo, isolated from the core business (De Anglis et al., 2018). In general, many mechanisms and activities in reverse supply chains are not yet fully understood or transferable to different contexts (Johnsen et al., 2014).

2.4. KEY GAPS IN LITERATURE

This thesis addresses three critical gaps in present-day literature. These will be presented in the following:

1. In contrast to the extensively attested financial potential of product recovery operations and product take-back, they have received only limited attention in current literature (De Anglis et al., 2018; Souza, 2013). Besides, there is a large gap between the theoretical financial benefits, and the reality in which take-back initiatives often are uneconomic (e.g., Sepúlveda-Rojas and Benitez-Fuentes, 2016). There is no explanation as to which factors influence the profitability of take-back initiatives. Due to academic and managerial relevance, the author has made it his task to close this gap in current literature. Since take-back systems can be enforced by law, they affect competing companies equally. Consequently, the purpose of take-back systems is not to compete with the core business of a company, but to run as profitably as possible (Bockholt et al., 2020). Therefore, the research published in this thesis aims to contribute to the practical and academic agenda through the following research question: *What are the factors that affect the financial performance of take-back initiatives, and how do they affect financial performance?(research question from research paper no. 1) (Bockholt et al., 2020)*

2. The majority of current research in the CE domain follows a greenfield approach by focusing on integrating circularity already in the design stage of products. Contrary to this, many

industrial companies are obliged to take a brownfield approach because they have to take back millions of products, which initially were not designed for circularity and, thus, are not subject to current CE research. The absence of historical data available from which an estimation could be derived in order to predict product return volume and quality, and on the other hand, the lack of sufficient knowledge about remaining product value and how to exploit it most effectively, address another gap. These two issues make a significant research gap that demonstrates how the inadequacy of data and knowledge challenge many manufacturing companies. Contrary to industry, nature exemplifies a well-functioning closed-loop system; it operates as a system of nutrients and metabolisms in which there is no such thing as waste (Bockholt et a., 2019; Braungart et al., 2002; Ryen et al., 2018). Although many authors praise the biological cycle (called biosphere) for its perfection and function (e.g., MacArthur 2013, McDonough et al., 2002), there is only one conceptual paper (Ryen et al., 2018), which uses biomimicry to conclude the biological cycle to the technical one. However, this is only done concerning biological search strategies for food vs. industrial search strategies for products. Furthermore, the paper is purely conceptual and does not work with empirical data. The author closes the gap in current literature by extending the model developed by Ryen et al. and including biological digestion strategies and industrial value recovery strategies as technical counterparts. In addition, the author tests the developed concept empirically using six embedded cases to derive further findings. The research question which the author aims to answer is: *How search, and digestion strategies from the bio-sphere are translated into the technosphere and used to inform strategies for product take-back?*

3. Resource effectiveness, in particular, has a powerful influence on the overall business case of take-back initiatives (Stahel, 2010; Macarthur, 2013; Benton et al., 2015). Reuse or remanufacturing as a recovery strategy outperforms recycling by far if sufficient functional product value remains at the end of the product's life (Sharpe et al., 2018; Benton et al., 2015;

Braungart et al., 2007). Motivated by his previous findings, the author intends to put his primary focus on exploring how information technology can be used to increase the effectiveness in EoL value recovery. The initial motivation for his research question arose from reviewing relevant academic papers, all of which highlighted the high potential of information and technologies that collect, share and process data as key enablers for the Circular Economy (Morlet et al., 2016, Rosa et al., 2020). One of the most recent literature reviews in this context is by Rosa et al. (2020). Here the authors reviewed 690 documents dealing with the intersection of the circular economy and information technologies in the context of Industry 4.0. After the exclusion of grey literature and non-English publications, 158 documents remained for closer examination. The authors have divided them into different categories based on Industry 4.0 technologies and Circular Economy concepts.

With regard to the research question: *"How can information technology be used to increase the effectiveness in End-of-Life value recovery?"* the author filtered out concepts that are on a higher, less technical level, such as CE Business Models; Digital transformation; Smart Services; Sup-ply Chain Management. Furthermore, the author considered disassembly to be a non-relevant category, as related literature substantially refers to the impact of digital technologies on the efficiency of the disassembly process. The author also excluded resource efficiency, as this concept is partly contrary to resource effectiveness (Braungart et al., 2007; Bocken et al., 2016). With regard to digital technologies, the author excluded additive manufacturing, as this technology does not relate to the resource effectiveness of existing EoL components but to the production of new components for maintenance and repair. In addition, the author did not consider simulation to be relevant. Simulation is a potentially important part of relevant concepts such as cyber-physical systems (CPS), but it is not directly meaningful on its own.

Consequently, the author limited the investigated concepts to remanufacturing, reuse, lifecycle management, and the Industry 4.0 technologies to *big data* and analytics, cyber-physical systems, *Internet-of-things*, and *I4.0* in generic terms. Through this second selection round, the body of relevant literature has shrunk to 20 academic papers, of which 10 are conference, and 10 are journal publications. The relatively high number of conference publications reflects the novelty of the topic. After reviewing all 20 relevant papers, the author found that none explicitly discusses the role of data on resource effectiveness; in other words, the jumps between resource loops. However, eight papers attest to the influence of data as an enabler of specific resource loops, four of which are based on empirical data. Barbosa et al. (2016) suggest that product condition data in the EoL phase allows informed decisions to be made about which products and components can be reused, remanufactured, or recycled. However, the authors do not empirically substantiate this statement and do not address the underlying mechanism. Sharpe et al. (2018) argue that lifecycle data about the product during its life span helps to make informed decisions about repair and component harvesting. They also do not elaborate further on the data, the mechanism, or a link to their empirical case. Rødseth et al. (2017) describe that life cycle data from the product, collected and analyzed in the context of predictive maintenance, helps to extend product life actively. Here, they give an example that refers to power consumption data and vibration data of the tested device in their case product. Yang et al. (2018) confirm Rødseth et al. (2017) 's finding, based on a case study, the authors show that data related to predictive maintenance can extend the lifetime of products by enabling more efficient maintenance and repair processes. However, in contrast to great promises made, no empirical examples can be found to illustrate how data functions as an enabler for increasing resource effectiveness. With his third work package, the author aim to bridge this gap in current literature, giving a holistic, empirically-based view on four resource loops and data as an enabler for transitioning between them. Figure 2-1 visualizes the four resource loops and the scope of the two concepts resource effectiveness and resource efficiency.

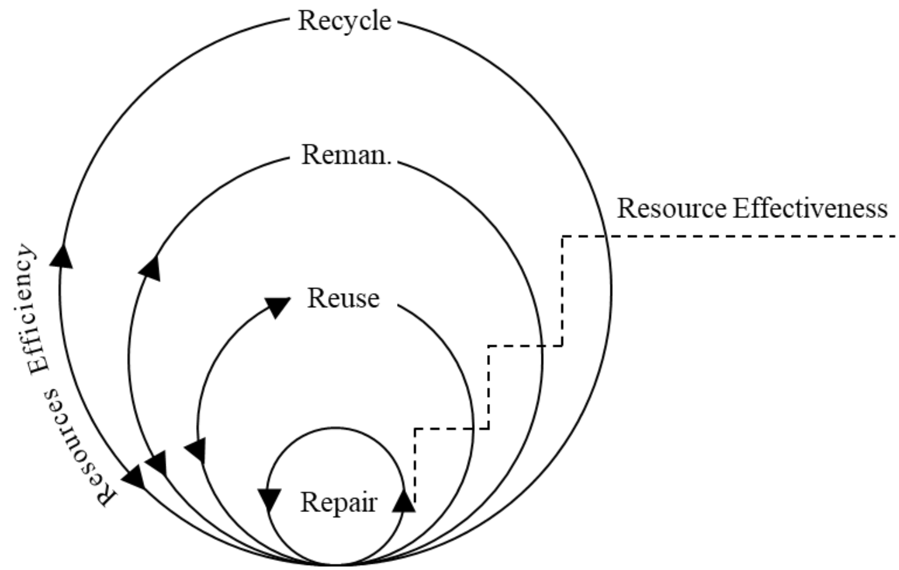

Figure 2-1 Resource Efficiency and Resource Effectiveness

CHAPTER 3. RESEARCH DESIGN

The central aim of this thesis is to create theoretical knowledge advancing the understanding of Circular Economy in operations and supply chain management simultaneously with advancing industrial knowledge and practice. Due to this dual objective, the project has been carried out in close industrial collaboration. The following chapter covers the research design. It addresses critical questions such as which research approaches have been employed to answer the three research questions, how those approaches have been applied, and how quality has been ensured.

3.1. RESEARCH APPROACH

3.1.1. RESEARCH PARADIGM AND METHODOLOGICAL APPROACH

With this thesis, the author pursues the overall goal to develop new knowledge, whereas the key performance indicator for this knowledge is how it contributes to academia and practice. Various definitions of knowledge are available, and the author is not going to create a comprehensive overview or analysis in the context of this thesis, albeit to argue for the relevance of his research the author needs to define what he understands when talking about knowledge as it determines the theoretical and practical contribution of the past three years of his professional life.

His interpretation of knowledge builds significantly on three key definitions. The first provided by Turban (1992), who defines knowledge as information that has been organized and analyzed to make it understandable and applicable to problem-solving and decision making. Scientific knowledge from a pragmatic perspective similarly addresses actionable and problem-solving capabilities, which, however, also need to pass validity/credibility and generalizability/transferability criteria, which in turn calls for a rigorous research process. A rigorous research process contains elements of research positioning in terms of relevance to the scientific community and to practice. Secondly, this positioning should be translated into researchable research questions, which guide the research; thirdly, these should be operationalized into research design and finally into a research process, which meets quality criteria for proper research.

A crucial dimension to this is to understand his academic “home” (Huff 2008) both in terms of positioning his findings, but certainly also in terms of defining appropriate outsets for it. Therefore, it becomes indispensable to have a clear overview of what has already been published. The author obtained this overview through scanning state-of-the-art literature in relevant research domains. Keeping track of relevant existing and new publications also inspired his research through suggestions for further research pointed out by other authors and provided fundamental constructs, which he used to build his analysis on. His key performance indicator, which the author uses to evaluate the research contribution is its generalizability. Especially in his domain of Operations Management and in the context of his in-depth casework, it has always been challenging to achieve and needed continuous attention.

The author sees knowledge generated by him as a contribution to existing knowledge, which implies that knowledge is cumulative. Based on the maturity of the domain, knowledge builds in different phases. When there is only a little knowledge available, and the field of research is rather new, the study will take an explorative character. Once a certain base, which identifies components in the field emerges, the research will move into a more descriptive phase. Once a good descriptive body of literature is available, it creates the foundation for analytical research. Analytical research finds correlations between variables and identifies how independent variables affect each other. The research will initially ask questions about what is in the area; once more knowledge is attained, this will move towards how questions and eventually asking “why it is so.”

There are different levels of knowledge in research. A fundamental element is a data, which consists of measurable facts that are gathered. Data turns into information once put into a system or context. Information can be used by creating a context by adding experiences. This enables interpretation regarding the applicability, effects, and other strength and weaknesses. Creating knowledge is the result of this interpretation. Due to the cumulative nature of knowledge and the above described sequential development of research fields, different research outputs will be seen. Usually, research projects start with a collection of facts, which have not been assessed prior. This is traditionally followed by an analysis of those facts, generalization, and eventually testing of those generalizations.

As mentioned above, a key performance indicator for generated knowledge is how it contributes to the existing knowledge present in relevant bodies of literature. To build his research contribution, the author started with an intended contribution, which entailed preliminary contribution objectives. Afterward, he applied reverse logic. This has been done by starting with the intended research contribution, asking the question:" what needs to be done, to reach this intended contribution?". Sequentially the author mapped existing practical and academic knowledge in the research area to decide for a suitable methodology.

To enable a basis for generalizability and to ensure research quality, the author ensured that the reader is able to follow the logic of his study and would theoretically be able to repeat it. To do so, he emphasized two key points.

1. Research steps need to fit together and it has to be possible to conclude how one step follows the other

2. Elements of research created in each step have to fit, so that for example, the available empirical material will suffice for answering the RQ, that analytical approach will give valid outcomes and so on

3.2. ACTION RESEARCH PROJECT AND THE ROLE OF THE PHD

Funding and hence framing of this research project did not allow for complete discretion by the researcher. Throughout the project duration, the researcher has been hired and co-financed by the case company. Hence, close industrial collaboration has been a framing factor. Another framing factor has been the academic expectations of the research project, contributing to academic knowledge building in the domain of operations and supply chain research. Those framing conditions helped to focus the project around an existing, relevant industrial problem. This is essential to ensure relevance in operations and supply chain management (Coughlan, Draaijer, Godsell, & Boer, 2016). On the other hand, the case company's expectations influenced the research design in the way that it raised the implicit expectation that the project contributes to improved Circular Economy practices through active participation in the case company's operations by the researcher. Hence, the project builds fundamentally on the two pillars, active involvement, and submersion of the research, in both practice and theory. In this context, interaction (Svenson, Ellström, & Brulin, 2007) and action (Coughlan & Coughlan, 2002) turn next to analysis and reflection into key criteria.

Even though the industrial nature of this project has set limitations on the choice of the case company, research theme, and expectations of tangible, practical improvements, the researcher maintained a high level of discretion regarding his position within the research domain, research opportunities to pursue, and how to pursue them. This discretion allowed for addressing a relevant theoretical as well as a relevant practical problem (Näslund, 2002). Since the outset of the project has been industrial, a critical first step has been to correlate the given practical problem with existing academic literature to potentially find theories, which are relevant for solving the monitored problem. Even though the researcher had a free hand in designing and conducting the project, an initial steering committee meeting has been held to align expectations of industrial (case company) and academic stakeholders (University). To ensure continuous alignment over the full 3-year project period, those meetings have been repeated on a quarterly basis. The main content has been updated on project progress as well as discussing preliminary findings and emerging opportunities. The steering committee meetings had an overall positive impact on the flexibility of the project as they allowed for continuous realignment. Furthermore, as a platform for discussions and reflections, they contributed to the quality of the research.

Based on the extent and engagement of industrial collaboration, field researchers can be categorized into four groups. These are 1. complete participant; 2. participant-as-observer; 3. observer-as-participant;

complete observer (Burgess, 2002). Throughout the project duration, the researcher shifted between different research modus, namely participant-as-observer and observer-as-participant. Even though there has been a natural pull from the organization to engage the researcher as complete participant, this has been prevented through a sharply formulated working contract as well as communications towards working colleagues within the organization, that the main purpose of industrial stay is research rather than other commercial activities. The chosen research roles match the actor approach, which was put forward by Arbnor and Bjerke (2008). It allows for close collaboration between the researchers and relevant individuals in the case organization. This again strengthens the depth and richness of collected data and is relevant for addressing the “how” questions of the research.

The continuous shift between the two research modes, participant-as-observer, and observer-as-participant, mirrors action research as an overall research setting. Within the last three years, the researcher’s role continuously alternated from being an active project team member or even project manager, directly responsible for results, to taking on the role of a reflective observer. This enabled the satisfaction of practical as well as academic requirements. The overall research design applied in the Ph.D. project is action research (Coughlan & Coghlan Action research for operations management, 2002; Näslund, 2002), albeit a majority of individual papers has been published through conferences and journals in the form of case studies (Yin, 2014, Voss, Tsikriktsis, & Frohlich, 2002). The chronological perspective has been retrospective. This retrospective approach can be used as an integrated element of an action research project. In such a situation, the case performs the function of a ´learning history´ and is used as an intervention to promote reflection and learning in the organization (Kleiner and Roth, 1997). The foundation of the research project is six individual papers, each of which comprises a unique research design and methodology. The focus of this chapter is, however, the overall research frame in which the six papers are embedded and how they are used to fulfill the overall research objective in the same way as answering the individual research questions.

3.3. CASE JUSTIFICATION

The fact that the researcher has been an integrated part of the case company, in many instances indistinguishable from regular employees with almost full access to sensitive data (e.g., Standard Unit Cost of all products; Sales numbers; Profit margins), meets one key aspect of doing empirical-based research, the one of obtaining sufficient access (Croom, 2009). As a circular economy and the taken research ankle, which focuses primarily on hard data, this was a key prerequisite to conducting the present research project. Having sufficient access to data is, however, not the only criterion for selecting meaningful case studies. Yin (2014) proposes five compulsory rationales for single-case design. Those are: critical, unusual, common, revelatory, and longitudinal. All five are relevant for justifying the selection of the case company. In the following, the author is going to briefly discuss the selected case company considering the five rationales.

As described in the introduction of this thesis (Chapter 1), reverse or circular supply chain are commonly present in today's industry, if supported by a reasonable business case or by the need for legal compliance. Today, where society is still at the early stages of a transition towards circular supply chains, and products have not been designed to be circular, a clear majority of discrete manufacturing companies are unable to run profitable reverse supply chains. Therefore, circular economy initiatives, such as take-back programs are largely nonexistent. The chosen case company offers the unique characteristics of running End-of-Life take-back programs in an experimental setting, accepting deliberately negative financial implications. This unique proposition opens the possibility to deduct exceptional theory and proves the unusual but critical nature of the case.

The chosen case company produces (Chapter 4) discrete manufacturing products. The produced products, as well as the present manufacturing technology, can be classified as common in the light of today's discrete manufacturing industry. This, in turn, supports the generalizability of findings.

The case is revelatory by nature, as the above-described nature of this unique case combined with the in-depth industrial collaboration, allows him to access information on a new phenomenon that was previously out of reach for academic investigation. Throughout the 3-year project duration, he had revelatory access to project team meetings, steering committee meetings, interviews across managerial decisions, internal- and archival data, substantiating the appropriateness of the case company as a single case.

A longitudinal perspective is attained as the 3-year duration in which the author has worked in different roles within the case company allows him to investigate historical developments within the different sub-cases in the case company. Besides, he had unlimited access to a case company's internal archive, which contains historical commercial and technical documents from 1945 to the present day (Paper 2).

In addition, the single case study approach is appropriate for the formulated research questions, as it allows the researcher to be at eye-level with project teams and decision-makers in the empirically rich and messy real-life environment where the experimental circular economy projects take place.

3.4. RESEARCH ACTIVITIES AND EMPIRICAL FOUNDATION

Although the overall research methodology of this Ph.D. thesis is action research (Coughlan & Coghlan, 2002), it does not reflect in a majority of the published research papers, as these were written retrospectively and thus mostly in the form of a case study (Voss, Tsikriktsis, & Frohlich, 2002). Only research paper number 5 has been written in an action research approach. The research was documented and disseminated by five research papers. Each paper contributes a specific part to answer the research questions and the research objective: Elevating Circular Economy from a CSR initiative to an industrial revenue stream. Table 3-1 links the five papers to the individually chosen research methods, data sources, and summarizes the research contributions of each paper.

Table 3-1 Link between papers and methods

Research Question	Paper	Method	Data-sources	Contribution
RQ1: What are the factors that affect the financial performance of take-back initiatives, and how do they affect financial performance? (Research Question answered in research paper 1; (Bockholt et al, 2020)	1	Embedded case study	Observations Archival Data Interviews Workshops	Identifying factors that affect the financial performance of End-of-Life takeback initiatives and discussing how they affect it.
	2	Longitudinal case study	Interviews Archival Data	Giving a historical context to how circular economy and the financial business case related to it emerged.
RQ2: How can search, and digestion strategies from the biosphere are translated into the technosphere, and used to inform supply chain strategies for product take-back? (Research Question answered in research paper 3 and 4; Bockholt et al., 2019)	3	Conceptual paper	Literature	Development of industrial supply chain strategies for facilitating the transition towards efficient and effective EoL value recovery.
	4	Multiple case studies	Observations Archival Data Interviews	Testing of developed strategies in real-life cases and development of a general framework to facilitate supply chain decisions.
RQ3: How can product data be used to increase the effectiveness in End-of-Life value recovery?	5	Design Science Research Embedded case study	Literature Active participation in workshops Observations Archival Data Interviews	Identification of the role and function of information and information technology as a key enabler for circular supply chain initiatives.

Figure 3-1 illustrates how different papers are linked to different data sources. Additionally, it provides an overview of the projects the author initiated and managed actively in the context of his action research approach over the three-year duration of the Ph.D. project. The individual cases shown in figure 3-1 serve as data sources for multiple papers. Key cases have also been analyzed individually in in-depth embedded single case studies. The author initiated four major industrial take-back and value recovery projects over the three-year Ph.D. duration. Namely: End-of-Life Product Take-back United Kingdom; End-of-Life Product Take-back Warranty; Resource Recovery Project Number 1 and Resource Recovery Project Number 2. The author has also actively been assigned the role of project manager for the initiated projects, some of which have been completed, and others are still ongoing, as shown in figure 3-1.

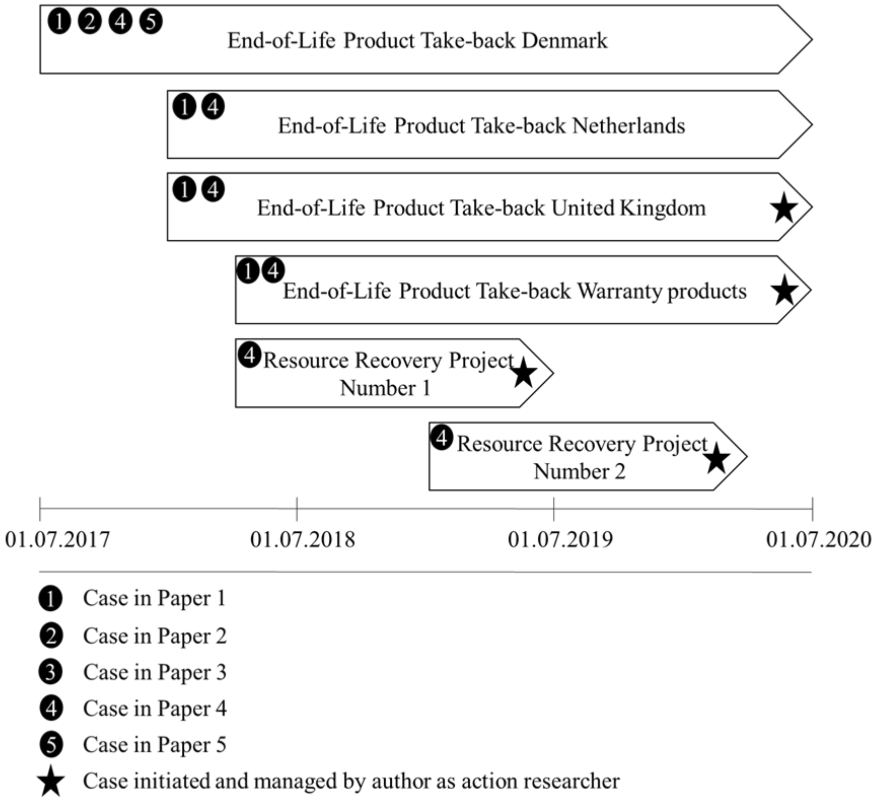

Figure 3-1 The link between industrial and research projects

To answer RQ1 the author builds on an embedded case study methodology as key source of data. He chose a multiple embedded case study methodology as he did not know at this point in time what the factors are and, therefore, could not build a survey instrument. Further, that financial performance could not easily be defined or identified from regular performance data. The author chose particular empirical cases to answer RQ1, as they allowed him to cross-analyze multiple take-back systems implemented in different countries, belonging under the same umbrella program of the case company. Due to this, he was able to hold particular factors (e.g., product type, market segment, disassembly efficiency) constant, while others (e.g., local legislation, reverse logistics, utilized resource loops) were left to vary as they would naturally (Meredith, 1998). The main contributing paper is research paper number 1, which unit of analysis are four take-back initiatives. The author identified and located relevant data sources through observations of project team meetings, semi-structured interviews with project team members and decision-makers, and workshops along the full financial value chain of the take-back initiatives. These sources have been used under the main focus of identifying relevant archival data sources within the data management system used by the case company (e.g., SAP, supplier contracts etc.).

The author used the definitions of resource effectiveness (Braungart et al., 2007) and Eco-Efficiency (WBCSD, 1992), a conceptual framework for answering RQ1. In order to give the reader a precise definition of resource effectiveness and the role of resource effectiveness in the context of the circular economy, the author invites the reader to refer to research paper number one of this thesis.

Research paper number 2 contributes to answering the research question by utilizing a longitudinal case study methodology revealing how the overall financial performance of take-back initiatives in the case company developed over its time being since 1945. Data sources here have been semi-structured interviews with senior employees as well as archival data from the company's internal historical archive.

Figure 3-2 illustrates the full product life cycle. The scope of RQ1 is within the highlighted circle. The unit of analysis is costs and earning related to the take-back and value recovery process as well as earnings-related to value recovery. The case narratives build on a rich empirical foundation spanning from shop floor workers in local plants to decision-makers from the management group of the case company.

The depth and quality of the collected data is a strength of the action research methodology applied. The following table 3-2 gives an overview of the stakeholders around the organization, which the author engaged with throughout the project to collect relevant data.

Table 3-2 Stakeholders around the organization

Function/ Hierarchical level	SVP	Director	SM	LPM	PM/SP	Op/Sa	Total
EHS	1	1			6		8
Manufacturing		1	2	2	4	18	27
Supply Chain		1		5	10	22	38
New Product Development	1	1	2	4	26		34
Quality	1	1	4	6	4		16
Purchase			1				1

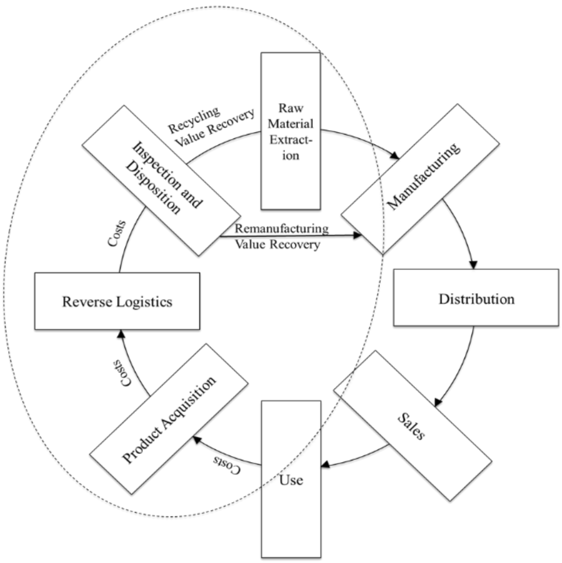

Figure 3-2 Research scope.

Service				1	1	18	20
Sales		1	1	1	3	16	22
Finance		1	2	4	3		10
Total	**3**	**7**	**12**	**23**	**57**	**74**	**176**

Note: SVP: Senior-vice president, SM: Senior Manager; LPM: Lead Project Manager; PM/SP: Project Manager/ Specialist; Op/Sa: Shop floor employees in Operations and Sales

The author utilized the concept of a mental research framework, as proposed by Yin (2015), as a critical concept to target his research questions. Throughout the research project, he interpreted the research framework as a broad set of behaviors rather than a tightly scripted interaction between him and any source of evidence. Along those lines, additional flexibility of the research framework was achieved through a dynamic and iterative creation, application, and refinement of the framework, which means that questions have been refined and retargeted based on the previously obtained information. This iterative process also contained refinement of the research questions, based on the richness of available data as well as unfolding relevance for the case company and the academic gap in the literature (Yin, 2015). The role of the mental research framework changed throughout the three-year project period. The author applied it more rigidly in the project beginning when he entered the case company. In this stage, it helped him to: identify existing take-back cases; gain an overview of the organizational structure; and to identify key stakeholders, especially relevant, due to personal interest and intrinsic motivation within the research area. In this initial stage of the research, the author has been perceived and introduced as a PhD researcher.

The later course of the project had its foundation in actions, which the author conducted actively to apply, test, and refine preliminary findings. He interpreted the mental research framework less rigid and more loosely in this phase, as by this point, his role was deeply embedded within the case company as a project manager. The framework was informally applied in his mind and helped him to keep track, as the risk of getting lost in the practical work as a project manager steadily increased. In this stage, he did not collect data through formal interviews but active participation in the project team and steering committee meetings.

The table below illustrates one of the applied mental research frameworks used in the context of RQ1.

Table 3-3 Applied mental research framework

Illustrative Research Protocol for RQ1
Topics and Protocol Questions
A. General Information outlining the operational context of the case company 1. When has the case organization been established? 2. How is the global organization structured? 3. What markets does the organization operate in? 4. What products are produced? 5. How is the ownership of the organization structured? **B. EoL product take-back initiatives in the case organization** 1. Were there past initiatives comprising reuse, remanufacturing or recycling of products? 2. How were those activities set-up? 3. Where in the organization have those activities been running? 4. How was the financial performance of those activities?

5 .	How was the financial performance accounted for and reported? (Databases; ERP systems?)

C. Existing EoL product take-back initiatives in the case company?

1 .	Is there any recycling, remanufacturing, or reuse initiatives ongoing today?
2 .	How are those activities setup?
3 .	Where in the organization are they running?
4 .	How is the financial performance of those activities?
5 .	How is financial performance accounted for and reported? (Databases; ERP systems?)

D. What are Costs/ Earnings associated with the different steps of the reverse supply chain?

1 .	What are Costs/ and earnings within product acquisition, and where is this data stored?
2 .	What are Costs/ and earnings within reverse logistics, and where is this data stored?
3 .	What are Costs/ and earnings within Inspection & Disposition, and where is this data stored?
4 .	What are Costs/ and earnings within Reconditioning? Moreover, where is this data stored?
5 .	What are Costs/ and earnings within Distribution and Sales, and where is this data stored?

Yin, R.K., 2015. *Qualitative research from start to finish. Guilford publications.*

Addressing research RQ2, the author builds on a combination of different research methodologies to build an understanding of efficient and effective reverse supply chain design based on the findings of RQ1. In his first research activity within this research question, reflected in paper number 3, he applies biomimicry as a methodology to exploit proven biological theories on circular flow in an industrial context. The data source for this conceptual paper has been a literature study, identifying and analyzing meaningful contributions from a more mature research domain and extrapolating the knowledge onto the identified research objective. The next methodology the author used to give a profound answer to the identified research question has been a multiple embedded case study methodology. He used six individual, embedded take-back and resource recovery cases from the case company to test the findings of paper number 3 in paper number 4 and to deduct critical learnings on how to use gained knowledge in a generalizable manner.

Finally, for addressing RQ3, the unit of analysis shifted from hard financial factors and supply chain design decisions towards investigating the role of data and data technology for increasing the effectiveness of End-of-Life value recovery. The unit of analysis has been data flow within a single embedded case study as well as relevant literature. At the beginning of the research project the case has not been existent within the case company, but has been iteratively build by the researcher and his project team by applying a design science methodology.

Even though each presented research paper builds on its research design, the following section focusses on how the research quality has been ensured encompassing the full Ph.D. project.

3.5. RESEARCH QUALITY

The general criterion for research quality must be the trustworthiness. Four different requirements used in social sciences are of relevance to determine the research quality: construct validity, internal validity, external validity, and reliability (Yin, 2015). Contrary to traditional research approaches, action research does not have to justify itself concerning alternative epistemologies and research approaches (Susman and Evered, 1978; Anguinis, 1993). Schein (1987) and Eden and Huxham (1996) state that quality in action research must be defined within its terms, particularly those which argue that the reflection and data generation and the emergent theories cannot be captured readily by alternative approaches. Hence, action researchers are reluctant to use the term validity, since it has connotations from positivist science; instead, ‘quality’ is preferred. (Reason and Bradburry, 2011). The author structure his research quality chapter in accordance with four dimensions identified by Levin (2003) for judging the quality of action research. These are participation; real-life problems; joint meaning construction, and workable solution.

3.5.1. PARTICIPATION

How well does the action research reflect the cooperation between the action researcher and members of the organization?

As the research content comprised sensitive data sources such as standard unit costs, component costs, sales volume, etc. the research required in-depth access to sensitive data sources within the case company. To achieve this, the researcher has been fully onboarded as an employee in the case organization. This comprises a valid working contract for the full duration of the research project, full access to all internal data management, and enterprise resource planning systems. In the three years, the researcher spent an average of three working days per week in the case company. The organizational rank of the researcher changed over the extent of the project from researcher to project manager as it became apparent that a change in status supports the researcher in managing stakeholders within the initiated action research projects. As shown in table x, the span of collaborating peers within the organization comprised 176 individuals from 9 different departments. The financial volume of the project managed by the researcher exceeded 2 million Danish kroner. The collaboration was structured through iterative steering and project team meetings within the individual projects as well as biweekly overall departmental team meetings. Additionally, the researcher participated in 7 team building seminars held in 3 countries, one of which he organized as host.

3.5.2. REAL-LIFE PROBLEMS

Is the action research guided by a concern for real-life practical outcomes, and is it governed by a constant and iterative reflection as part of the process of organizational change and improvement?

The applicant and initiator of the present project is an industrial case company. Negative business cases in their circular economy initiatives as well lack of understanding in how to design reverse supply chains for End-of-Life products and how to facilitate the transformation towards more circular supply chains motivated them to approach the Ph.D. supervisor at Aalborg University. Preliminary to this project, the researcher worked as a researcher at the hosting University from where he actively collaborated with industrial and academic peers to support scoping the project.

3.5.3. JOINT MEANING CONSTRUCTION

Is the process of interpreting events, articulating meaning, and generating understanding a collaborative process between the action researcher and members of the organization?

The research has been conducted in close collaboration with members of the case organization. To achieve joint meaning construction, the researcher had bi-weekly, 4-hour workshops with the senior manager, heading the environmental center of excellence, of which the circular economy team is an integrated unit. Those meetings provided a continuous platform for presenting preliminary results as well as analysis and discussion. The contribution of the senior manager involved has been acknowledged by co-authoring one of the central papers of this thesis (paper 1). In addition to that, the researcher sourced industrial knowledge and perspectives from ongoing dialogues with his colleagues in the Circular Economy team of the case company (1 Lead manager & 1 Project manager).

Furthermore, to ensure validity and conformity with company-internal accounting guidelines, all developed business cases have been co-developed with an internal accountant. To the extent the knowledge dissemination and the discussion beyond the researchers’ project team, he also presented preliminary findings in company internal presentations, such as the “Materials Day 2019”, where he presented the research in front of over 200 employees across all technical departments involved in product and process design. The outcome of this discussion was a fruitful dialogue and discussion with five participating employees.

3.5.4. WORKABLE SOLUTION

Does action research engage in significant work, does sustainable change come out of the project?

Within its 3-year duration, the research showed a clear impact within the case company, measurable through hard financial data. Findings related to RQ1 have been used to design, build, and run a new End-of-Life product take-back initiative in the UK market, which proves to be significantly more profitable than previous take-back initiatives. The initial Danish initiative has a cost-neutral business case, meaning that recovery costs equal the monetary value recovered per product. The new UK initiative, initiated, established and run by the researcher has a positive business case, whereas value recovered proves to be 47,6% higher than recovery costs, which is reflected in a positive business case. Additionally, this new initiative collaborates with a local charity project, providing jobs for two employees with limited working capabilities.

Findings related to RQ2 have been used within the case company to restructure the resource recovery initiatives. Building on the knowledge extracted and extrapolated from biological foraging patterns, a new approach to identify resource recovery potentials have been developed and introduced within the case company. Again, this reflects directly in the financial performance of the resource recovery initiative. In the time span from 2016 to 2018, the case company was able to recover assets worth 8,5 million DKK through its resource recovery project. After adopting a new resource recovery approach based on the findings as mentioned earlier in 2019 alone, a total amount of 13,8 million DKK was recovered. Out of which the action research was directly responsible for over 90%.

CHAPTER 4. RESULTS AND DISCUSSION

The following chapter presents and discusses the findings of the research questions, which underly this thesis. It follows the order of work packages that have previously been presented in the chapter on research design. The presentation and discussion of each work package follow the same structure: 1. research context, 2. summary of the findings of the related papers, 3. additional findings, and reflections, which are not present in the paper, as they are gained from the implementation of the findings, 4. theoretical implications, 5. practical implications.

The research context gives insights into the problem, which this research tries to solve and gives an understanding of the usefulness of the research findings. The additional findings and reflections provide insights two-fold. Out of a practitioner's point of view, it presents and discusses the implications of solutions, which have been implemented in the industry based on the research results and hence contribute to the validation of the results. Additionally, out of a theoretical perspective, in some cases, it indicates new research avenues. The below figure illustrates the Ph.D. research journey.

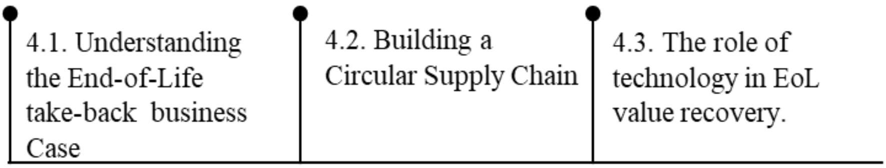

Figure 4-1 Layout of this chapter

4.1. UNDERSTANDING THE CIRCULAR BUSINESS CASE

The following sections present and discuss the findings related to research question 1: "*What are the factors that affect the financial* *performance of take-back initiatives, and how do they affect financial performance?"* The central paper is paper number 1, whereas paper number 2 supports the setting of the research context.

4.1.1. RESEARCH CONTEXT

For a detailed overview and description of the key drivers of the circular economy and an explanation of its fundamental concept, the author of this thesis encourages his readers to read research paper number one.

Apart from the ecological gains, a circular economy offers the prospect of securing the availability of resources and the financial exploitation of the residual product value, thus creating an ecological-financial win-win scenario (Bockholt et al., 2020; R. Geyer, T. Jackson, 2004). In contrast to the auspicious financial potential, in practice there is a clear indication that take-back initiatives are not profitable (Sepúlveda-Rojas et al., 2016).

From Grundfos' foundation in 1945, circular practices on design, repair, reuse, and re-manufacturing have been central to the founders' beliefs. Since these early days, the sustainability agenda of the company relied heavily on its founder's ideas and vision. It was not an explicit core agenda, but it was implicitly present in the organization's core values of "responsible thinking," "efficient use of resources," and "paying back to the community." Throughout globalization of the world marked and Grundfos transition from a small local pump producer to substantial multinational cooperation, it's focus on circular economy vanished, as other product and business development agendas became more promising as well as a better fit to the new company structure. (For more information, please read paper number 2). In 2001 repair and service have mostly been outsourced, and related initiatives shut down. Ten years later, motivated by social and environmental advantages, but also by increased volatility of the resource marked Grundfos reinitiated its Circular Economy agenda, operationalized through an EoL product take-back initiative. As many other documented cases, Grundfos struggles to exploit the financial potential of EoL take-back even though life cycle assessment (LCA) studies and employment of an inclusive workforce confirmed the positive environmental and social performance of the EoL take-back initiative, the financial business case was negative.

Grundfos established its first take-back initiative in 2012 in its home market in Denmark, later on in the Netherlands (2018) and in the United Kingdom (2018). The focused EoL products are domestic heating pumps, which are high volume / low-value products, with a long lifetime. As heating pumps have been subject to continuous product development over the last 30 years, multiple design changes have been conducted. Due to substantial investment into automated production equipment, the company experienced design change limitations, which lead to only three significant changes encompassing the full product platform- The EoL products are retrieved from the marked through fixed pick-up boxes at an independent wholesaler. EoL products are tossed in the boxes by installers, who are customers of the wholesalers. Conventionally, installers install new products at the end-customers site and take old products back. Neither installers nor wholesalers are financially incentivized to participate. The incentive is purely based on social responsibility, marketing, and branding opportunities. The returned EoL products are shipped via an external logistic provider from the wholesaler to Grundfos, where they are disassembled by flex workers (workers with limited working capabilities) in a manual disassembly line. The extracted components are sorted according to their raw material content and sold into the raw material marked. The newest of the three product platforms, which is still in production today, has been tested for remanufacturing and is currently subject to a first pilot, where two remanufactured components will be reintegrated into products sold to a large strategic customer.

On the cost side, a closer look at the business case of Grundfos' take-back initiative shows that the costs of logistics, sorting, and disassembly are higher than the profits generated by recycling recovered raw materials. Processes required to close the resource cycle are exclusively manual and not nearly as optimized as processes from Grundfos' core competence of production. On the positive side of the balance sheet, one can see that the raw material prices strongly limit earnings since recycling is currently the only option rolled out in a larger scale (remanufacturing still in the pilot phase)—a combination of relatively high costs and low earnings results in a negative overall business case.

To better understand and potentially improve the financial performance of Grundfos, EoL takeback initiative, a simple balance sheet for each national take-back initiative (UK, NL, DK) has been built and by analyzing and comparing the cases key factors that affect the business, the case was deducted. The next section summarizes and discusses the findings based on paper 1.

4.1.2. SUMMARY AND DISCUSSION PAPER 1

The methodology applied builds upon an in-depth multiple case study within Grundfos national take-back initiatives in Denmark, the United Kingdom, and the Netherlands. For a detailed account of the financial calculations and the case data, please refer to paper number 1.

Because the different cases belong to Grundfos' overarching global take-back program, the author was able to hold particular factors (e.g., product type, market segment, disassembly efficiency) constant, while others (e.g., local legislation, reverse logistics, utilized resource loops) were left to vary as they would naturally (Meredith, 1998). The cross-case analysis of the three take-back programs unveiled seven distinct factors, which impact the financial viability of take-back programs. Those can be split into factors impacting the earnings of the financial balance sheet and factors impacting the cost side of the balance sheet. Earnings, as explained in the context description above, are related to how sufficient resources are re-looped. The more value recoverable at the EoL, the higher the resource effectiveness. The first identified factor in this context is the chosen resource loop. Recycling is placed at the lower end of the scale as it only recovers raw-material value and reuses at the upper end as it recovers full functional value. Hence, the effectiveness of resource use rises, the more functional value can be recovered. The second and last factor that affects resource effectiveness is supply chain capabilities. The ability to feed materials or components back into the own supply chain has a positive impact on the business case. E.g., recycling aluminum within the own supply chain ensures the transparent quality of aluminum and cuts out the profit margin or metal traders.

In terms of resource efficiency, five factors are affecting the costs of the system. Those five can again be divided into two groups. In contrast, the first group is logistic costs, and the second group handling costs. Three of the five factors are placed within the logistic costs. The first of which is the business model. Here a transaction-based business model is on the lower end of the scale. Transaction based business models place the product ownership into the hands of the end-customers. This turns reverse logistics into a rather complex undertaking. Product return depends on the end customer's goodwill, and in a transaction-based setup, there is no access to EoL products for the manufacturer. Therefore, reverse logistics must be artificially initiated by the end customer. Moving towards a serviced business model through maintenance contracts or even through pay by performance business models allows for continuous access to EoL products by the manufacturer, which decreases complexity and costs in reverse logistics. The second factor impacting logistic costs for EoL products is legislation. Depending on the material composition of EoL products, national and international waste-transport directives can have a significant impact on the reverse logistic costs. Depending on the legal waste classification high taxes, rooted in a worldview in which waste means a negative load for each nation rather than an opportunistic view, apply for international waste transfer. The third factors affecting the logistic costs of take-back initiatives are consolidation capabilities. Natural consolidation, which occurs, e.g., when large customers purchase and operate a high volume of products, which can be returned from centralized locations. Having small decentralized customers, purchasing and operating little product volumes results in a complex reverse logistic setup in which small batches of EoL products are sent from many decentralized locations, which disables scalability of logistics and results in high reverse logistics costs.

The second group of factors impacting the resource efficiency of take-back initiatives is the handling costs. Here the author identified two major factors contributing to handling costs. The first factor is the local salary level. Since handling processes such as sorting, disassembly, and remanufacturing are uncharted territory for conventional producers and at the same time pose specific technical challenges, such as heterogeneous product quality, handling processes are often manual. The process maturity is far below that of conventional production. Therefore, labor cost plays a significant role as a factor influencing the handling costs. The second factor which strongly affects the handling costs is the homogeneity of returned products. Dealing with multiple product qualities (product type and – condition) requires more complex

Table 4-1 Overview of factors impacting the take-back business case (copied from paper I)

		Factors impacting the Takeback business case				
		Factor	Negative Impact	↔		Positive Impact
Resource effectiveness		Ressource Loop	Dispose	Recycle	Reman.	Reuse
Resource effectiveness		Sup. Chain Capabilities	None	Third Party	Direct Supplier	In-house
Resource efficiency	Logistic cost	Business Model	Transaction based	↔		Servitized
Resource efficiency	Logistic cost	Legislation	Bureaucratic	↔		Supportive
Resource efficiency	Logistic cost	Consol. Capabilities	No Consol.	↔		Consol.
Resource efficiency	Handling cost	Salary Level	High	↔		Low
Resource efficiency	Handling cost	Homogen. of Returns	Hetero.	↔		Homo.

sorting and disassembly as well as remanufacturing processes and decreases the overall product handling efficiency significantly. On the other hand, homogeneous returns allow for streamlined disassembly processes and minimized sorting efforts. Table 4 2 summarizes the key factors identified in this work package.

As described in chapter 3, even though paper no. 1 has been written as a retrospective case study, the overall research design has been action research. The Ph.D. research has been actively responsible as a project manager and initiator of a new take-back program in Grundfos. The researcher applied the above framework to select a suitable supply chain, national manufacturing plant, and customer. The result was the initiation of the take-back program UK. To validate and test the findings in practice, the author measured the financial performance of the take-back DK program against the take-back UK program. In doing so, one can see an improvement in the financial performance of 47,6%. The improvement is currently solely due to improvements within the area of resource efficiency. The research motivated Grundfos to engage in first steps towards resource effectiveness by initiating a small-scale remanufacturing project for two key components, which is planned to go live in 2021. Preliminary results indicate that remanufacturing only 10% of a returned pump potentially increases the profitability by over 300%.

Although the developed framework provides useful information for decision-makers in where and how-to set-up a take-back initiative, there are certain limitations to the applicability of the framework which needs to be considered. Resource effectiveness, remanufacturing, or reuse have not been considered throughout the product design phase. Hence, for many components, resource loops are blocked due to wear and tear patterns, which do not allow the recovery of functional value or the need for destructive disassembly.

4.1.3. ADDITIONAL INSIGHTS AND REFLECTIONS

In the following, additional insights and reflections are presented, which have been gained after the publication of paper no 1.

Even though resource efficiency and resource effectiveness have been presented as two necessary development directions, they play a significantly different role for the business case of take-back initiatives. Even if a manufacturer achieved a very high EoL product handling efficiency, the profit would always be limited by the resource effectiveness (how much value am I able to recover?). As the raw material value tends to be significantly smaller than the functional product value, this proves to be a significant limitation.

OEM manufacturers create value through the design and manufacturing of products, rather than the mining of raw materials (that is the task of suppliers such as mining companies, raw material handlers, or recyclers). In the manufacturing industry, expertise lies in the design and production process. Because the knowledge and intellectual property of the product design and production process and the forward production and sales channels, in which components or products might be reintroduced, are in the hands of OEM manufacturers, the functional value can best be restored by them. Take-back initiatives only start to become financially relevant and neutralizable for OEM manufacturers once they partly unlock the recovery of functional product value through inner resource loops such as remanufacturing or reuse. If manufacturers operating take-back initiatives are unable to achieve better resource effectiveness than the recovery of raw material value, the business case will always be sub-optimal compared to the business case of specialized waste handlers, as those operate highly efficient fully-automated mechanically destructive shredding and sorting processes within an economy of scale. Hence from a financial perspective, the recycling efficiency will be higher when it is outsourced to a specialized waste handler. Being locked into low value recovering resource loops, such as recycling, is a massive problem in the industrial transformation towards the circular economy, as Grundfos and other manufacturers moved billions of products into the market over the last decades, which have not been designed for remanufacturing and represent a large legacy problem. Hence it is the manufacturer's task to work on solutions, which exploit the functional value of those products as far as technically possible

Resource efficiency aligns with incremental supply chain and operations efficiency improvements, such as lean-principles or automation. In contrast, resource effectiveness calls for a disruptive change in product design. Design for disassembly - remanufacturing or -reuse is unlike any conventional product design strategy. The previous industrial focus in product design has been on resource efficiency, which calls for using less material with lower financial impact, considering only one product lifecycle. An example could be replacing metal components with composite ones. Resource effectiveness, on the other hand, calls for thinking in multiple lifecycles, which requires a raw material choice and a component design that allows multiple lifecycles. Here composite materials would not be suitable as they are subject to aging and thermal wear and tear. Metals would potentially be the better choice. Following, there might be a fundamental contradiction in design for resource efficiency and design for resource effectiveness. Hence, the author proposes the interdependence of both design strategies as relevant for further research.

Another promising research avenue are synergies between EoL takeback and handling and traditional forward production. Grundfos UK produces highly customized water solutions for large customers, which are exclusively engineered to order. Due to re-occurring delays in delivery of custom components, Grundfos UK faced multiple production stops, where the workforce needed to be redistributed towards non-directly-value adding tasks (e.g., cleaning the shop floor). On the other hand, Grundfos UK also frequently experienced situations where sick leaves of individuals resulted in a shortage of workforce and delay in delivery times towards customers. Having a local disassembly area in place now allows to move workforce when needed from the disassembly area to the conventional production area, and in case of stock-outs production, workers can directly continue value-creating tasks by disassembly of EoL products. Hence, the author proposes the interdependencies between manufacturing and EoL product take-back as a further relevant field of research.

Circular economy initiatives are often motivated by a triple bottom line perspective. Social, environmental, and economical. Even though the author decided on the economic aspects as most relevant for his research, he also conducted a Life-Cycle-Assessment. His motivation to-do so was rooted in his role as a project manager. Since customer-facing communication and branding arguments of the take-back initiative have been environmental, the author wanted to measure its environmental performance to mitigate the risk of “not doing good.” The result of his LCA study (not published) was that the Grundfos takeback initiative saved around 50% processing water and 10% C02 compared to conventional EoL handling in Denmark (which is recycling by external waste handlers). Those savings can be attributed to the manual disassembly process, which saves processing water compared to automated shredding and density separation processes (density separation in water basins) and internal recycling of aluminum. Especially the internal recycling of aluminum proves to save water and C02 as it cuts out one additional melting process, which would take place at the waste handler. The LCA indicates a mismatch within the triple bottom line. External recycling shows the best financial performance, whereas internal, manual recycling shows the best environmental performance. Arguably recovering functional value could align environmental and financial goals.

4.1.4. THEORETICAL IMPLICATIONS

When reviewing the state-of-the-art literature, the author's original experience in Grundfos concerning the intransparent and hard-to-understand business case turned out to be a more general academic problem than a problem specific to Grundfos using state-of-the-art literature. The business cases of take-back systems are intransparent and difficult to understand (Hopkinson et al. in 2018). At the outset of this research, there has been no empirical study available, which offered real-life insights into which factors impact the business case of take-back initiatives or how they do it (Nygaard et al., 2020). The general lack of empirical research regarding the economic performance of take-back initiatives has been pointed out by multiple researchers working in the domain (De Los Rios et al., 2017; Lieder and Rashid, 2015). The author closes this gap by analyzing earnings and costs in detail and utilizing a cross-case analysis to deduct factors impacting those. The following figure illustrated the systematic research process applied by Nygaard et al.(2020).

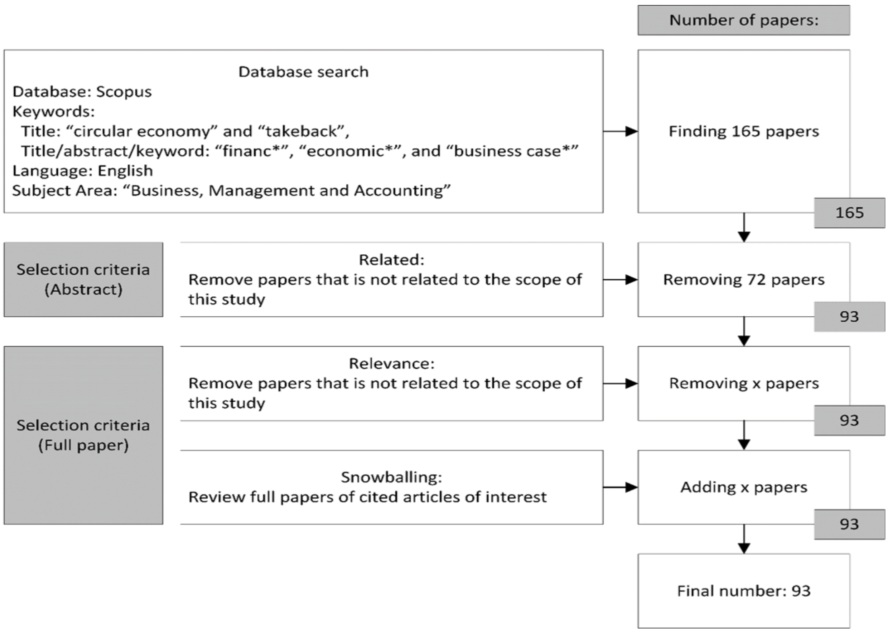

Figure 4-2 Research process

4.1.5. PRACTICAL IMPLICATIONS

Chronologically WP1 encompasses the first work, which the author conducted within Grundfos. Establishing the complicated business case of take-back initiatives based on literature (e.g., Guide and Wassenhoven 2002) has been a fundamental first step for the Ph.D. research. In the first step, the author developed an excel tool, encompassing all earnings and costs in a layout, which allows the quick adaption of the tool to different national setups. This initial excel allowed Grundfos the first time to get a realistic overview of the financial performance of their take-back initiatives (at this point, take-back was running in DK and NL). Together with internal programmers, the tool has been further developed into a Power BI application, which updates fluctuating variables automatically (e.g., resource prices). Based on the findings of WP1, Grundfos changed it is the take-back strategy and initiated programs in the UK and later in Argentina. Contrary to previous take-back programs UK and Argentina both have a positive business case.

WP 1 identifies and advocates the importance of resource effectiveness. Moving from recycling to remanufacturing became a key agenda for Grundfos. After the release of preliminary findings, a first technical feasibility study for the remanufacturing of critical components was successfully conducted in 2018. Based on the positive results, Grundfos currently performs a large-scale remanufacturing test of 10.000 circulation pumps in cooperation with a large OEM customer. Furthermore, understanding the meaning and importance of resource effectiveness motivated Grundfos to engage in new academic collaboration, e.g., MADE take back.

4.2. BUILDING A CIRCULAR SUPPLY CHAIN

As discussed in the introduction to this thesis, many of today's discrete manufacturing firms find themselves in a dilemma in their transformation from a linear to a circular supply chain. On the one hand, they experience acute and increasing pressure from various sides: from the society in which a strong environmental movement is forming (e.g., Fridays for Future); from the raw material market, as critical materials are coming to an end (e.g., Indium, Tin); from competitors, as young, innovative companies are able to gain a competitive advantage through a circular economy and from national as well as supranational legislators, who demand prolonged producers responsibility for the end-of-life phase of products (e.g., WEEE directive). On the other hand, many discrete manufacturers face a legacy problem. Millions of products are reaching the end of their life somewhere out there in the market, which was neither designed for value recovery (e.g., design for disassembly, design for remanufacturing, etc.) nor sold in a circular business model, which makes it challenging to locate them. The special challenge of large discrete manufacturing companies is that, unlike young companies, they are located in a brownfield. The product design and business model of already produced and sold products cannot be changed in retrospect. The majority of current research in the CE domain follows a greenfield approach by focusing on integrating circularity already in the design stage of products. There is a clear research gap regarding strategies for search and value recovery processes for large discrete manufacturing companies facing the stated brownfield, legacy problem. With work package number two, The author is with this thesis specifically targeting this legacy problem of large discrete manufacturers. He takes the most perfect closed loop ”nature” (biosphere), as an example, and cross-fertilize strategies for the search of EoL products for value recovery and interdependencies between both in the industrial context (technical cycle). The following sections present and discuss the findings related to research question 2: “*How can search, and digestion strategies from the biosphere are translated into the technosphere and used to inform supply chain strategies for product take-back?”* The principal, relevant papers are paper number 3 and paper number 4. Whereas paper number 4 is an extension of paper number 3, which test the built theory with empirical cases.

4.2.1. RESEARCH CONTEXT

As described in research paper number 3: “*The natural ecosystem is an eternal cycle, which iteratively recycles its major nutrients, such as carbon, hydrogen, oxygen, and nitrogen*” (Bockholt et a., 2019). Actors within this cycle encompass living being from the top to the very bottom of the food chain. The currency that is the driving force behind the biological cycle is energy in the form of calories. The vitality of an organism depends on a calorie surplus (absorbed kcal >= consumed kcal). In nature, hunters and gatherers extract calories from food through the digestive process but searching and handling food consumes calories. To achieve a positive calorie balance, they use different search and digestion strategies depending on habitat and food quality.

Already millions of years before the existence of mankind, the biosphere was the only all-encompassing cycle (McDonough & Braungart, 2002, Bockholt et al, 2019). To learn more about how and why human intervention has unbalanced the biosphere and why the opening of a second cycle, the technosphere, is necessary, the author of this thesis asks his readers to refer to research paper number three in the appendix (see Bockholt et al., 2019).For this reason, it is necessary to introduce a second, technical cycle (technosphere) in addition to the biological cycle (biosphere). The currency that is the driving force behind the Technosphere is monetary profit. The vitality of an organization depends on a surplus of money (income >= expenditure). Industrial organizations create financial turnover in take-back initiatives through the EoL value recovery process (e.g., recycling, remanufacturing, reuse), but reverse logistics and handling (e.g., sorting, disassembly, remanufacturing, redistribution) also consume monetary assets. To achieve positive profitability, companies apply different search (e.g., take-back schemes) and EoL recovery strategies (e.g., recycling remanufacturing, reuse) depending on the condition and quantity of EoL products. The costs caused by search, reverse logistics, and handling of EoL are key performance indicators that describe the efficiency of the reverse supply chain. Optimizing reverse supply chain efficiency is the effort to reduce those costs while maintaining the financial return on value recovery activity (*being better within a specific resource loop*). Resource effectiveness, on the other hand, describes the effort to optimize the return on value recovery activity by maximizing recoverable value (*jumping inwards between resource loops*). As discussed in WP1, it has not yet arrived in a significant part of the manufacturing industry. Today, take-back programs are often small-scale CSR initiatives, which are often artificially kept alive by organizations for marketing and branding reasons (Bockholt, 2020).

Compared to the technosphere, the biosphere is relatively well understood. Search, and digestion theories are subject to an extensive literature body that has its beginnings in the research of Emlem as well as Mac Arthur and Pianka in 1966. Natural intelligence includes the intelligence of nature that has been created by neural connections in the brain of living beings but also evolutionary intelligence of species (Gaudl and Bryson, 2018). To get a better understanding and definition of natural intelligence the author asks the readers of this thesis to refer to research paper number 4.

In order to benefit from the knowledge that has been enlarged by evolution in nature over millions of years, the author applies a biomimicry methodology. Biomimicry focuses on the cross-fertilization of natural intelligence from the domain of biology into the technical domain. . Biomimicry has already been used conceptually to utilize biological knowledge for finding new solutions to challenges in circular supply chains (see Ryen et al., 2018). For a detailed summary of the work of Ryen et al., the author of this thesis kindly invites the readers to refer to his research paper number three. He extends the results of Ryen et al.; creating the first holistic biomimicry model for circular economy (see Bockholt et al., 2019). The research question which the author aims to answer by the cross-fertilization of natural intelligence is:

What are the key design parameters and contingencies of efficient and effective EoL value recovery?

4.2.2. SUMMARY AND DISCUSSION PAPER 3,4

In this chapter, the author will summarize and discuss Paper 4 and Paper 5 of this Ph.D. thesis. Paper 4 uses biomimicry as a method to create a conceptual model and on a theoretical level to take a first mathematical model from the field of biology and translate it into the industrial context. Paper 5 is an extension of paper 4 in which he tests the model as well as the first application of a simple mathematical model in an industrial context on six embedded case studies.

The financial success of EoL take-back programs depends on two main factors. The profitability of the value recovery initiative (e.g., recycling, remanufacturing, reuse) and the number of EoL products returned from the market. In the following, the author draws a parallel between the strategies of companies searching for EoL products and the strategies of predators searching for prey (1). Furthermore, he draws a parallel between industrial value recovery strategies and natural digestion strategies (2).

A. From biosphere search strategies to Technosphere search for take-back products

Search strategies of hunters and gatherers can be divided into three categories. Cruise searcher; ambush searcher or saltatory searcher. 1. cruise searchers move continuously through their environment in search of prey. Examples are the tuna or the peregrine falcon. This search behavior is known in biological circles as an active search. 2. ambush searchers, or also called "sit and wait" searchers, stay in one place, often for relatively long periods. They wait for prey to move into their range and then strike from ambush. Examples of ambush searchers are herons and rattlesnakes. This type of prey search is also categorized as a passive search in the relevant literature. 3. saltatory searchers. This saltatory search strategy includes elements of cruise and ambush search strategies (passive and active search behavior). Creatures using this strategy actively search for areas with high prey chances. Once they have found a promising area, they change their strategy from active to passive and ambush potential prey (O'Brien et al., 1990). These three biological search strategies can be translated and applied in the context of the technosphere. A first conceptual model was published by Ryen et al. (2018). The active search for food can be interpreted in the context of the Technosphere as the active search for recoverable EoL products. Here, employees of a company actively search internal or external scrap yards or warehouses for EoL products that are suitable for value recovery. This is not a fixed supply chain or take-back program but a case to case initiative. The passive search for food can be interpreted in the context of the Technosphere as the passive search for recoverable EoL products. This is similar to the establishment of a traditional take-back system. Here the respective organization builds up a fixed reverse supply chain in the form of a take-back program. At the beginning of the reverse supply chain, the organization passively waits for the supply of EoL products by its customers through a pick-up location. The saltatory food search can be interpreted in the context of the Technosphere as a mixed search behavior of active and passive elements. Industrial organizations actively explore markets where the establishment of a passive take-back system is particularly lucrative. This behavior can be observed mainly in organically growing take-back initiatives in various international markets.

B. From Biosphere digestion strategies to Technosphere process strategies for value recovery (research question from research paper 3; Bockholt et al., 2019)

The following introduction is largely borrowed from research paper number three (written in italics). *Biological organisms use various digestive strategies. These are not necessarily genetically pre-programmed, but species are able to adapt their digestive strategies to external conditions. The decisive factor here is the quality of the food to be digested. In the biosphere, the quality can be determined by the caloric density. The authors' research is limited to the two polarizing ends of the spectrum of digestive strategies: rapid digestion and slow digestion. Rapid digestion is used when the caloric density of food is particularly low, as organisms increase the volume of food to be digested in order to absorb sufficient calories despite sparse caloric density. Since the capacity of the digestive system is limited, the flow rate must be accelerated. The short gut-retention-time does not allow to extract all the calories contained in the food. Only the calories that are easily digested are absorbed. Organisms use slow digestion strategies when the caloric density of the food to be digested high. Compared to food with a low caloric density, the volume of the food may be smaller and remain in the digestive tract longer. The long dwell time allows for high effectiveness in accessing the nutrients. The author employs biomimicry to draw a parallel between digestion strategies in nature and EoL value recovery strategies in the industry. Digestive strategies have been optimized throughout evolution to maximize the calories extractable from food (excess calories = vitality). EoL value recovery strategies, on the other hand, must be optimized to maximize the recoverable value of EoL products (profitability = vitality)(Bockholt et al., 2019).* As described in WP1 and in research paper number one, EoL product value exists in two forms: materials value and functional value (Kumar, 2010).

The author defines the resource recovery loops in recycling, remanufacturing, and reuse. Technical possibilities to use the different loops strongly depend on the quality (physical properties) of the EoL products. If, for example, due to outdated technology or heavy wear and tear, there is no remaining functional value, the recycling of raw materials is the only technically possible value-recovery option. There is a strong correlation between the existing product value (material or functional) and the feasibility of the different resource loops. To get a detailed description of this correlation and the different resource loops per se, the author of this thesis asks his readers to refer to research paper number 3 (see Bockholt et al., 2019).   Figure 4-3 contrasts the Biosphere and the Technosphere.

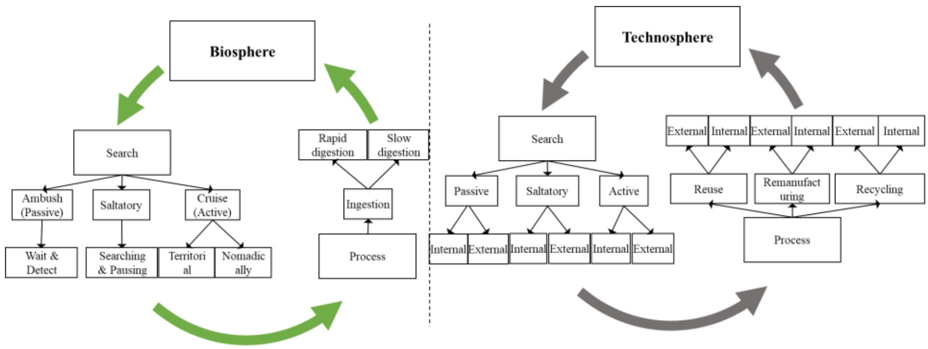

Figure 4-3 Framework for search and digestion strategies (copied from paper IV)

A first example of how to operationalize the concept presented above is the transfer of mathematical models established in biological research over the last century. The author has chosen the mathematical optimal-diet model by O’Brien et al., which was previously identified by Ryen et al. as particularly suitable (O’Brien et al., 1990; Ryen et al., 2018).

For a detailed derivation of the mathematical model and the transfer author made into the context of the technosphere, please refer to papers 4 and 5. Paper 4 describes, in particular, the mathematical derivation and paper five the application to empirical case studies. Table 4-2 gives an overview of the optimal diet model of O’Brien et al., from biology, the theoretical translation by Ryen et al. (2019), and the revised

Table 4-2 Overview of the optimal diet model of O'Brien et al., (copied from paper III)

Optimal Diet Model - Biology	*Translation of ecological model parameters (Ryen et al. 2019)*	*Revised Translation for Circular Economy initiatives*
$\frac{E_n}{T} = \frac{E}{T_S + T_H}$	$\frac{E_n}{T} = \frac{E}{T_S + T_H}$	$\frac{T_n}{C} = \frac{T}{C_S + C_L + C_H}$
$E_n = Energy\ intake$	$E_n = Net\ profit$ (\$)	$T_n = Turnover$ (\$)
$T = Feeding\ time$	$T = Foraging\ time\ (s)$	$C = Process\ costs$ (\$)
$T_S = Searching\ time$	$T_S = Search\ time(s)$	$C_S = Search\ costs$ (\$)
$T_H = Handling\ time$	$T_H = Shred\ or\ Diass.time\ (s)$	$C_H = Handling\ costs$ (\$) $C_L = Logistic\ costs$(\$)

translation by the author. The revision of the author´s translation has been made based on insights gained throughout WP1.

In the following, the author has empirically tested his mathematical model using six take-back case studies in Grundfos. Table 4-4 shows an overview of the critical characteristics of the six case studies. For more detailed case description, please refer to paper number 4. Translating the biological optimal foraging theory into a technical context shows how knowledge can be shared interdisciplinary. In nature, the optimal diet. The model provides the opportunity to predict the food choice of species by its caloric profitability. Translated and applied to the Technosphere, the "optimal diet" is a part of the financial profitability of the examined CE initiatives. Following the Pareto maximizes financial profit while minimizing the time required to create a turnover. Take-back DK and especially NL show a profitability factor below zero, which means that Grundfos is currently losing money on the initiatives and need to focus on efficiency and effectiveness optimization (if possible) before scaling:

1. Takeback Warranty
2. Resource Recovery No. 1
3. Resource Recovery No. 2
4. Takeback England
5. Takeback Denmark
6. Takeback Netherlands

Apart from the translation and application of the "optimal-diet models" as key-finding of this WP2, the empirical testing of the cross-fertilized knowledge reveals critical findings of the different EoL product search and value recovery strategies, which can be used by industrial organizations running circular economy initiatives, to build a balanced portfolio. The findings are summarized in Table 4-4, for a detailed account and discussion, please refer to paper number 5.

The industrial organization operating EoL take-back systems can apply multiple search strategies simultaneously. Passive search strategies have fixed reverse supply chains (e.g., take-back systems) and, therefore, a low degree of flexibility and a relatively high degree of efficiency. Active search strategies (e.g., internal resource recovery screenings) are one-off, discrete events, not aimed at target markets with continuous returns. They show a high degree of flexibility, whereas the supply chain efficiency is low. The trade-off between efficiency and flexibility ends in favor for flexibility. A comparison of active and passive industrial foraging strategies shows that active strategies have better financial performance. Even though the reverse supply chain costs per product are higher, the turnover generated by the resource recovery initiative is far higher. The reason for this is that employees searching actively for EoL products are incentivized by monetary profit and hence prioritize EoL product categories such as red-alert, slow mover, or warranty products which all represent a high remaining functional value and allow for profitable digestion strategies such as remanufacturing or reuse. In contrast to the relative profit that can be generated per product, the picture is different when looking at absolute profit. The absolute profit over a more extended period is significantly higher for CE projects with a positive passive CE strategy. This is mainly due to the high quantity of usable EoL products and the lower operating costs of the more mature reverse supply chain. These observations can be explained by the fact that active resource recovery initiatives are specifically looking for new products with a high functional value that can be regained through high value recovering resource loops such as remanufacturing or reuse. Since the search, logistics, and handling costs are relatively high, this filter is necessary to guarantee a financially successful project. The primary motivation of the Case company to carry out this kind of project is financial. Passive initiatives are more focused on quantity, as their motivation is not necessarily monetary, but also preventive to changes in the current legislation (WEEE) and for environmental reasons. However, the minimum requirement to be achieved is a neutral business case. 3. Saltatory search strategies occur in the maturing process of take-back initiatives when new markets are explored and tested for their potential through pilot trials. It is a flexible strategy that has only low fixed resources tied up in a formalized reverse supply chain due to its immature nature, thus reverse supply chain costs are often higher, but it allows flexible strategy changes. The level of structure could be described as semi-structured. The following table 4-3 summarizes all previously stated findings and thereby gives a comprehensive overview.

Table 4-3 Characteristics of industrial Search- and Digestion Strategies (copied from paper IV)

Search Strategies

	Active Search Strategy	Saltatory Search Strategy	Passive Search Strategy
Supply Chain Efficiency	LOW (discrete event)	MEDIUM (potentially scalable)	HIGH (optimized supply chain)
Supply Chain Flexibility	HIGH (one-off event)	MEDIUM (temp. SC.)	LOW (long-term SC.)
Search costs	HIGH (man. Screen.)	MEDIUM (small scale)	LOW (establ. SC.)
Return Volume	LOW (discrete event)	MEDIUM (experiment)	HIGH (establ. SC.)
Scale	LOW (one-off event)	MEDIUM (potent. scaleable)	HIGH (industrial scale)

Digestion Strategies

	Recycling of Raw materials	Remanufacturing of components	Remanufacturing of entire products
Resource Effectiveness	LOW (material value)	MEDIUM (funct. value partly)	HIGH (full functional value)
Handling Costs	LOW (destructive)	MEDIUM (partly non destr.)	HIGH (non destructive)
Turnover	LOW (limit. mat. value)	MEDIUM (funct. value partly)	HIGH (full functional value)
Quality requirements	LOW (raw materials)	MEDIUM (partly funct.property)	HIGH (full functional property)

Table 4-4 extensively summarizes the utilized case studies. For a detailed, written description, please refer to research paper number four in the appendix.

Table 4-4 Case study overview (copied from paper IV)

	Case 1 Takeback Denmark	Case 2 Takeback Netherlands	Case 3 Takeback England	Case 4 Takeback Warranty	Case 5 Resource Recovery No.1	Case 6 Resource Recovery No.2
Location	External	External	External	Internal	Internal	Internal
Age	6 years	2 years	< 1 years	< 1 years	discrete	discrete
Search Strategy	Passive	Passive	Saltatory	Saltatory	Active	Active
Product size	small	small	small	small	medium	medium
Product Age	5-25 years	5-25 years	3-7 years	0-2 years	8 months	3 years
Product condition	strongly used	strongly used	used	little use/ new	new	used
Returns (annually)	2000	1000	10.000	10.000	/	/
Returns (discrete event)	/	/	/	/	5.777	181
Market potential (units)	70.000	35.000	750.000	50.000	/	/
Digestion Strategy	Recycling	Recycling	Recycle/ Reman.	Rec/Reman/Reuse	Reman	Reuse
Optimal Foraging Index	0,89	0,49	1,92	13,23	10	10

4.2.3. ADDITIONAL INSIGHTS AND REFLECTIONS

One insight that the author has gained by examining the longitudinal development of take-back initiatives in Grundfos is the chronological evolution of search strategies. In the initial phase of take-back, only active search strategies can be observed. If the active search is successful, Grundfos strived to reproduce the financial success and explores possibilities to build a permanent supply chain. If the returns are continuous (e.g., warranty returns) and the digestion process (recycling, remanufacturing or reuse) is profitable, Grundfos will change the strategy from active to passive, once a passive take-back program is profitable, Grundfos naturally initiates efforts to expand from the first market to other national markets in its effort to strive for higher profits. This search strategy can be described as saltatory.

Another finding that the author derives from the empirical case studies is that there is a clear link between search and digestion strategies. Active search for EoL products, which have a high degree of flexibility but are much more cost-intensive, is mainly focused on products that are still high enough in quality to allow the recovery of functional value. This can be substantiated by the fact that active initiatives (e.g., Grundfos resource recovery project) are exclusively financially incentivized. Therefore, executing employees are continually striving to select projects with the highest possible turnover. Projects that include the recovery of functional value will prevail. Low value recovering digestion strategies such as recycling, in contrast, are often uninteresting due to the inefficient supply chain with active search strategies. For this reason, a targeted search is done for products that meet the requirements for the recovery of functional value (low wear & tear; young age). Figure 4-4 illustrates the relationship between search and digestion strategies. The break-even line indicates that specific strategies need to be coupled in order to enable economic viability.

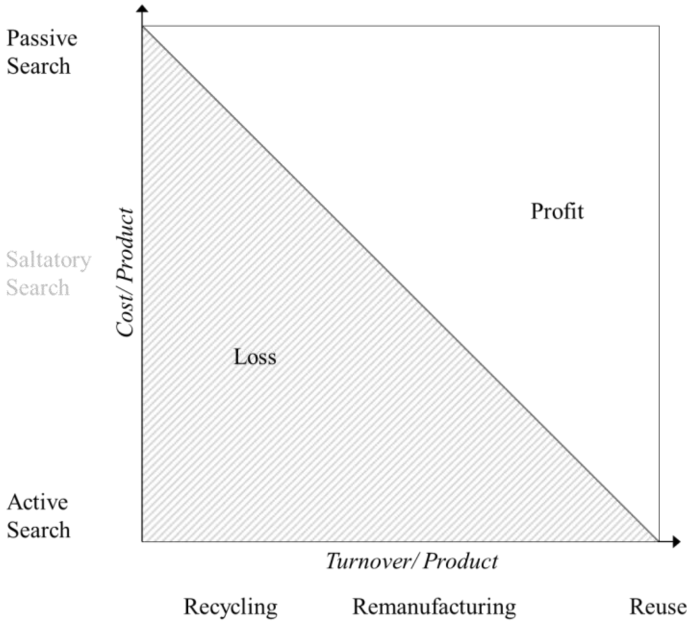

Figure 4-4 Search and digestion strategies relationships

The categorization of take-back initiatives according to the model of biology proved to be helpful in Grundfos, especially in the current transition from a linear to a circular economy. Initial efforts to set up a passive take-back program failed due to its poor financial performance. This can be attributed to two different issues. 1. Low efficiency: the low level of maturity of the processes in the reverse supply chain. Sorting and disassembly were initially simple manual processes that were not optimized. Processes in the reverse supply chain have different technical requirements than processes in the forward supply chain (Bockholt et al., 2020). 2. Low resource effectiveness: Grundfos and other companies, for whom remanufacturing is new territory, must acquire knowledge about the re-manufacturability of their products. This includes technical studies on the material properties, wear, and the remaining lifetime of the components or products. Also, a technical remanufacturing process must be developed and a process to reintroduce the components into the traditional supply chain. In order to gain enough time to build up the necessary process maturity and still obtain the financial “license to operate” for Circular Economy in Grundfos, active search strategies were formulated in the context of a newly formulated “Resource Recovery” project. The high financial gains that could be achieved by the active search and the recovery of functional value compensated for the relatively small losses caused by the low process efficiency of the reverse supply chain and the low resource effectiveness in the first passive initiatives.

As described above, through the six empirical case studies, explicit connections between the choice of search and digestion strategy in the technosphere can be identified. Following the example of biology, they can be explained by the striving to optimize vitality (vitality in the Technosphere corresponds to positive financial profitability; vitality in the biosphere corresponds to the excess of calories). Thus, it can be observed that active search strategies, which are characterized by an inefficient supply chain and are therefore costly, are exclusively linked to digestive strategies that recover a high degree of functional value and thus a high financial turnover.

A relevant perspective, which has not been published yet, is the relationship between the digestion- recovery strategy and the MVT (marginal value of time). The MVT describes the loss in value per unit of time spent awaiting completion of the recovery process. Joseph Blackburn et al., describe in their paper “Reverse supply chains for commercial returns” the role of MVT as a key decision-making factor for designing a suitable reverse supply chain (2004). The authors state that returned EoL products with a high MVT require a responsive reverse supply chain (optimized for speed) and products with a low MVT, an efficient reverse supply chain. The author argues that the relevance of MVT is directly related to the chosen recovery option. Destructive recovery options (recycling- raw material value recovery) destroys the functional value of a product and its components. The recovered raw materials are not subject to value degradation over time. One could even argue that there is a long-term tendency of raw material prices to rise (MacArthur, 2013).

On the contrary non-destructive recovery of functional value (e.g., remanufacturing or reuse) is very well subject to value degradation over time, which can be caused by components such as electronics, which lose their functional properties relatively quickly or through changes in the market such as technological innovations in new competing products. Following Blackburn's line of thought, assessing the MVT of returned products is critical in choosing the appropriate reverse supply chain layout (2004). Choosing a responsive supply chain layout implies the recovery of functional value. This aligns well with key findings of this thesis, which propose an active search strategy (responsive supply chain) as the best fit for functional value recovery (slow digestion) and a passive search strategy (efficient supply chain) as best fit for fast digestion strategies (recovery of raw materials, e.g., recycling). Overall the alignment of Blackburns and the author´s theory gives an additional validation of the results of this thesis. Figure 4-5 illustrates the correlation between product development clock speed, which directly relates to MVT and available resource loops.

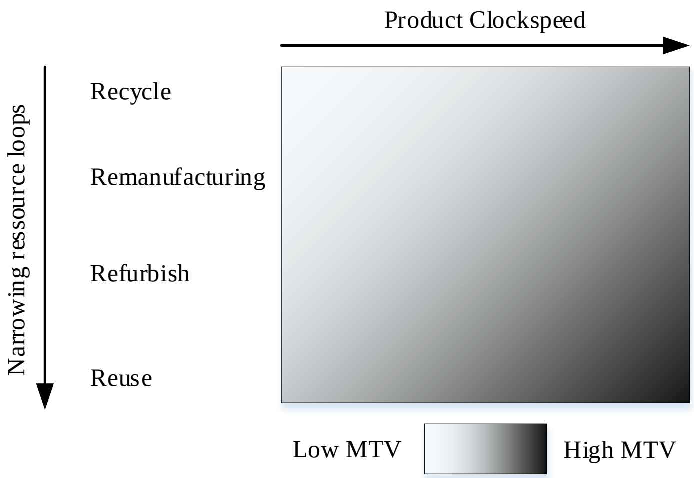

Figure 4-5 Resource loop MVT correlation

It is essential to acknowledge that this first holistic translation of biological foraging models into the *technosphere* must be regarded primarily as a door opener for further research projects. On closer examination, the exemplary transfer of the optimal diet model (equation) is mathematically identical to the financial performance indicator of profitability (equation). This validates the author´s theory and proves that his translation of the variables is correctly interpreted. On the other hand, it suggests that the application of biomimicry may well be able to draw on a profound knowledge base from nature, which in turn promises new insights for the still largely unexplored field of the circular economy.

4.2.4. THEORETICAL IMPLICATIONS

Before the present work, only one author has been working on uncovering synergies between knowledge developed throughout evolution in the domain of biological foraging strategies and take-back strategies for industrial manufacturers in the technosphere. Whereas this first research solely focused on search strategies. The presented research closes the full circle by including biological digestion as a role-model for value recovery strategies in the technosphere and interdependencies between both. Furthermore, the author was able to prove his theory of search and digestion strategies by applying them in a real-life industrial context. With the developed conceptual model and the empirical validation, the presented research opens up a promising area for further research, and the author encourages practitioners to continue along this path, utilizing models and theories from biology to accelerate the understanding of CE.

4.2.5. PRACTICAL IMPLICATIONS

The author was able to apply active search strategies within the context of the Grundfos resource recovery project, which was managed by the Ph.D. candidate from 2018 to 2019. After taking over the project, he changed the focus from identifying potentials for recycling to a targeted search for functional value recovery (e.g., red alerts, -slow movers, warranty etc.). This shift has been done to align the active search strategy with a suitable digestion strategy. Based on this strategic change, the author was able to recover more than 13,8 million DKK, which is more than Grundfos was able to recover in the same initiative in the previous years (2016- 2018) together. Furthermore, he was able to cluster ongoing circular economy projects according to the applied search digestion strategies in order to create a balanced circular economy portfolio. A portfolio, which on the one hand is financially feasible due to high-value recovery active search projects and on the other, allows for experimenting and ongoing efficiency improvements in the passive project, like Grundfos EoL take-back initiative. The presented findings, as shown in research paper 4, are generalizable and can be applied in different industrial, manufacturing contexts.

4.3. THE ROLE OF DATA AND TECHNOLOGY IN CIRCULAR SUPPLY CHAINS

The following sections present and discuss the findings related to research question number 3:” How can product data be used to increase the effectiveness in End-of-Life value recovery?” This chapter is primarily based on research paper number 5. Paper number 5 builds on a design science methodology, where a data-driven solution is built and empirically tested, aiming at optimizing resource effectiveness using product condition data.

4.3.1. RESEARCH CONTEXT

In WP1, the Ph.D. candidate identified several factors that are responsible for the financial performance of EoL take-back initiatives. These are: Resource loop; supply chain capabilities, business model; legislation; consolidation capabilities, salary level, and homogeneity of returns. All of which either impact the efficiency of the reverse supply chain (ii. efficiency) or the effectiveness of how value is recovered (i. resource effectiveness) (Braungart et al., 2007).

The concepts of resource efficiency and resource effectiveness are sufficiently explained in research paper number one (see Bockholt et al., 2020).

A closer look at the results of WP1 (Paper No.1) and WP2 (Paper No.4) shows that resource effectiveness, in particular, has a powerful influence on the overall business case of take-back initiatives. Reuse or remanufacturing as a recovery strategy outperforms recycling by far if sufficient functional product value remains at the end of the product's life (Bockholt et al., 2020; Sharpe et al., 2018; Benton et al., 2015; Braungart et al., 2007). Motivated by his previous findings, the author decided to put his primary focus on exploring how information technology can be used to increase the effectiveness of EoL value recovery. The initial motivation for the research question arose from reviewing relevant academic papers, all of which highlighted the high potential of information and technologies that collect, share and process data as key enablers for the Circular Economy (MacArthur, 2016, Rosa et al., 2020). One of the most recent literature reviews in this context is by Rosa et al. (2020), here the authors reviewed 690 documents dealing with the intersection of the circular economy and information technologies, in the context of Industry 4.0. After the exclusion of grey literature and non-English publications, 158 documents remained for closer examination. The authors have divided them into different categories based on Industry 4.0 technologies and Circular Economy concepts, as summarized in table 4-5.

CE-related classification items		I4.0-related classification items	
CBMOD	Circular Business Models	AM	Additive Manufacturing
DIGIT	Digital Transformation	BDA	Big Data and Analytics
DISAS	Disassembly	CPS	Cyber-Physical Systems
LIFEC	Lifecycle Management	IOT	Internet of Things
RECYC	Recycling	SIM	Simulation
REMAN	Remanufacturing	Generic	Any I4.0 technology
RESOU	Resource Efficiency		
REUSE	Reuse		
SMSER	Smart Services		
SUPCM	Supply Chain Management		

Table 4-5 lists of classification items

Source: Rosa et al., 2020

Regarding his research question: "How can product data be used to increase the effectiveness in End-of-Life value recovery?" the author filtered out concepts that are on a higher, less technical level, such as CE Business Models, Digital Transformation, Smart Services, and Supply Chain Management. Furthermore, he considered disassembly to be a non-relevant category, as related literature substantially refers to the impact of digital technologies on the efficiency of the disassembly process. The author also excluded resource efficiency, as this concept is partly contrary to resource effectiveness (Braungart et al., 2007; Bocken et al., 2016). Concerning digital technologies, the author excluded additive manufacturing, as this technology does not relate to the resource effectiveness of existing EoL components but to the production of new components for maintenance and repair. In addition, he did not consider simulation to be relevant. Simulation is a potentially important part of relevant concepts such as cyber-physical systems (CPS), but it is not directly meaningful on its own.

Consequently, the Ph.D. candidate limited the investigated concepts to remanufacturing, reuse, lifecycle management, and the Industry 4.0 technologies to big data & analytics, cyber-physical systems, Internet-of-things, and I4.0 in generic terms. Through this second selection round, the body of relevant literature shrank to 20 academic papers, of which 10 are conference, and 10 are journal publications. The relatively high number of conference publications reflects the novelty of the topic. After reviewing all 20 relevant papers, the author finds that none explicitly discusses the role of data on resource effectiveness; in other words, the jumps between resource loops. However, eight papers attest to the influence of data as an enabler of certain resource loops, four of which are based on empirical data. Barbosa et al. (2016) suggest that product condition data in the EoL phase allows informed decisions to be made about which products and components can be reused, remanufactured, or recycled. However, the authors do not empirically substantiate this statement and do not address the underlying mechanism. Sharpe et al. (2018) argue that lifecycle data about the product during its life span helps to make informed decisions about repair and component harvesting. They also do not elaborate further on the data, the mechanism, or a link to their empirical case. Rødseth et al. (2017) describe that life cycle data from the product, collected and analyzed in the context of predictive maintenance, helps to extend product life actively. They give an example that refers to power consumption data and vibration data of the tested device in their case product. Yang et al. (2018) confirm Rødseth et al. (2017) 's finding, based on a case study, the authors show that data related to predictive maintenance can extend the lifetime of products by enabling more efficient maintenance and repair processes. However, in contrast to great promises made, no empirical examples can be found to illustrate how data functions as an enabler for increasing resource effectiveness. None of the state-of-the-art papers analyzed that deal with digitization in the circular economy focus on the jump between resource loops (resource effectiveness), but rather deal with efficiency improvements within a resource loop (resource efficiency). None of the above examples used resource effectiveness as a central concept. Statements or findings referring to digitization as a key that unlocks resource loops are not part of the central discussion in any of the papers. Rødseth et al. (2017) are the only authors to give more detailed data requirements needed to prolong product life through predictive maintenance, but the authors do not cover any other resource loops. With the third work package, the author aims to bridge this gap in current literature, giving a holistic, empirically-based view on four resource loops and data as an enabler for transitioning between them.

4.3.2. SUMMARY AND DISCUSSION PAPER 5

In this chapter, the Ph.D. candidate will discuss the final paper of this thesis, paper No. 5. Paper number 5 uses a design science methodology to create a solution proposal for the poor financial performance of the Grundfos EoL value recovery process. The solution proposed is iteratively refined and finally implemented through a pilot study. This explorative research phase is followed by an exploitative phase in which generalizable, academic findings are deduced by using a case study methodology. As described above, the research focuses of this work package is the impact of data and data managing technologies (i.e., digital technologies) on the resource effectiveness of take-back initiatives. Its goal is to understand where and how data acts as an enabler for the jump between resource loops. The author contributes to today's "brownfield" situation in the Danish manufacturing industry, which brings unique challenges. A legacy of millions of products is currently in circulation, which is not designed for disassembly or reuse. Currently, most of these are recycled for the recovery of raw materials. The Ph.D. candidate systematically investigates, using an iterative design science method, which product and condition data are relevant to optimize the chosen resource loop. Furthermore, he uses the collected knowledge to derive inputs for greenfield product design. His approach is not characterized by forcing digital technologies top-down to the application in the context of a circular economy. In contrast, he uses a bottom-up approach. The candidate investigates the data requirements that must be met to achieve a specific resource loop without artificially forcing the application of digital technologies. He explores the point where digitization becomes essential to further increased resource effectiveness. It is undoubtedly logical that in the same or a similar way as in traditional forward manufacturing, digitalization brings incremental increases in process efficiency through more comprehensive, faster, and better data processing. However, it is not the author´s interest to study, observe, or describe such incremental process improvements. Figure 4-6 visualizes the precise research scope of WP 3.

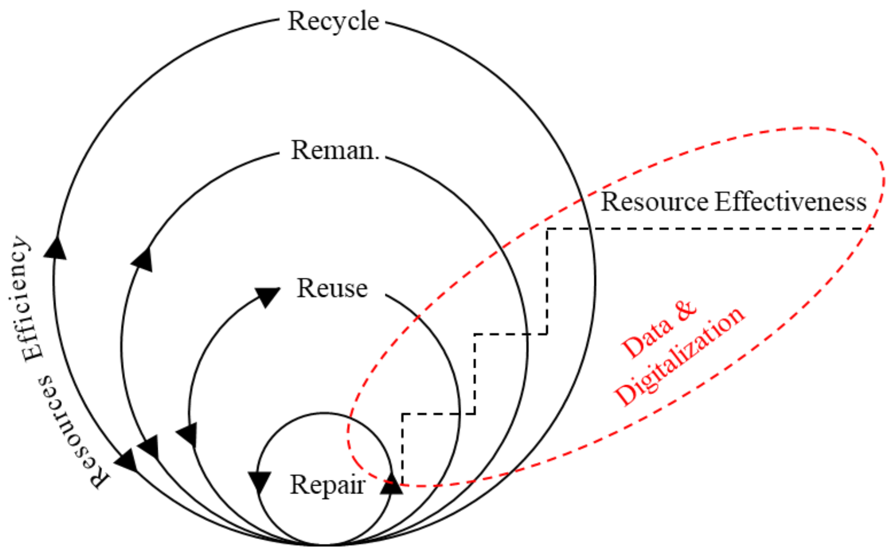

Figure 4-6 Research scope

The author used a design science method to combine the practical design of a solution for a real-life industrial problem with theory development (Holmström et al., 2009). It allows him to engage in problem-solving while simultaneously developing scientific contributions actively. The underlying logic of design science is that new generic designs will have practical relevance (Chaudhuri et al., 2020). The author can more easily crystallize and realize knowledge accumulation through a design science approach (van Aken et al., 2016). His design science approach differs from current action research because it explicitly creates a solution artifact (Holmström et al., 2009). Design Science has an (i) explorative and an (ii) explanatory phase.

i. The explorative phase consists of solution incubation and solution refinement. Solution incubation (research phase 1a and 1b) is used to build up an initial understanding of the research problem at hand and to develop an initial solution proposal based on this, which is detailed enough to be implemented but most likely incomplete. In the following solution refinement phase (research phase 2a and 2b), the previously developed solution proposal is iteratively tested, evaluated, and improved if necessary. If present, unintended side effects are also addressed. This iterative phase continues until no further design improvements of the solution proposal can be achieved. Figure 4-7 visualizes the explorative research process.

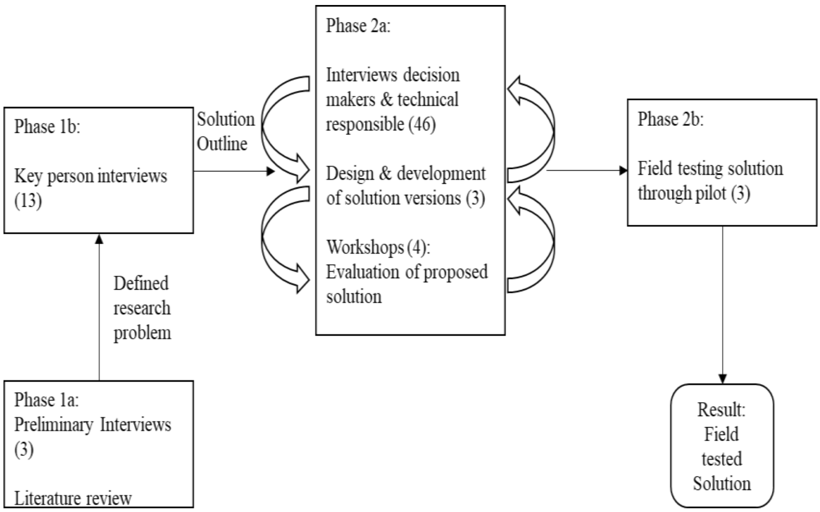

Figure 4-7 Explorative research process

> The critical phase, in turn, also consists of two phases: Explanation 1, in which the author evaluates the developed artifact from a theoretical point of view. With this, he aims to develop a substantial theory. Its contextual dependence limits this theory. The design science methodology also foresees an explanation 2 phase, which aims to develop formal theory, if possible. Here, the generalizability of the theory in a broader sense is intended (Holmström, Ketokivi, and Hameri 2009). This phase is not in the scope of this thesis as presented findings will always be context dependent within the scope of industrial take-back initiatives.

In the following, the results of research phase 1 are presented. For more detailed information and interview questions, please read research paper 5. Starting from the initial symptom of a weak business case, the author discovered in a preliminary interview that even with high-efficiency improvements of the reverse supply chain, the business case could hardly become noticeably positive, since recycling is the only available resource loop. Recycling solely recovers raw material value, which is very small compared to the functional product value. The second round of interviews with technical product experts revealed that the underlying root course of being locked into the recycling loop is an absence of information about the exact version of a product. Previously, products were only sorted by product type, but within a product type, there were numerous product versions over a life span of more than ten years, where potential errors were eliminated, or the design was changed to increase efficiency in the manufacturing process. Some of these engineering design changes allow remanufacturing, and some do not. Without knowing the exact product version, remanufacturing is not possible. Based on this, the identification of the exact product version and an analysis of the engineering changes for remanufacturability was introduced as an initial solution proposal.

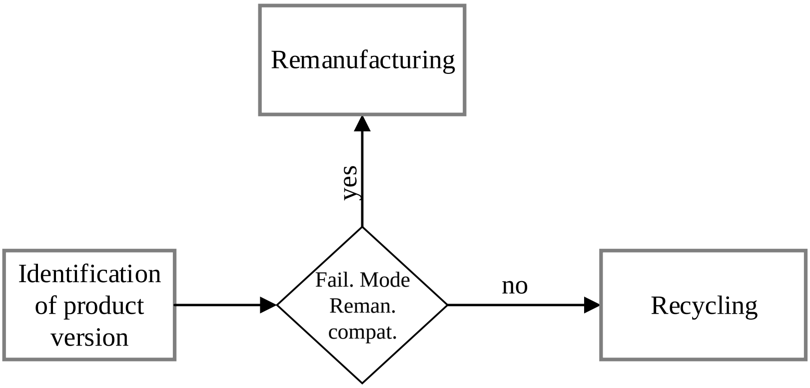

Figure 4-8 Preliminary solution proposal

After the Ph-D. candidate developed an initial solution proposal, he iteratively tested, evaluated, and improved it in the second exploratory research phase "solution refinement." This was done in a total of six iterations. This process took place as an integrated part of the case company. The researcher took the role of being the project manager, and in total, more than 46 project team meetings were held with various functions of the company, such as Quality, Product Development, Manufacturing Technology, and Environment Health & Safety. For a detailed description of the six cycles of the solution refinement process, please refer to research paper number 5. In the course of the six cycles in which the author iteratively evaluated and improved the initial solution proposal, he was able to unlock remanufacturing and reuse in addition to the existing recycling loop. With the help of the technical product responsible engineers, the author identified various data requirements that must be met in order to operate remanufacturing and reuse. In addition, he developed a process that can fulfill these data needs through physical and electronic analysis steps (*Figure 4-8*).

In the following, the author presents the final result of the developed solution proposal, which marks the endpoint of the iterative refinement process. He names the final solution proposal 3R process in the following:

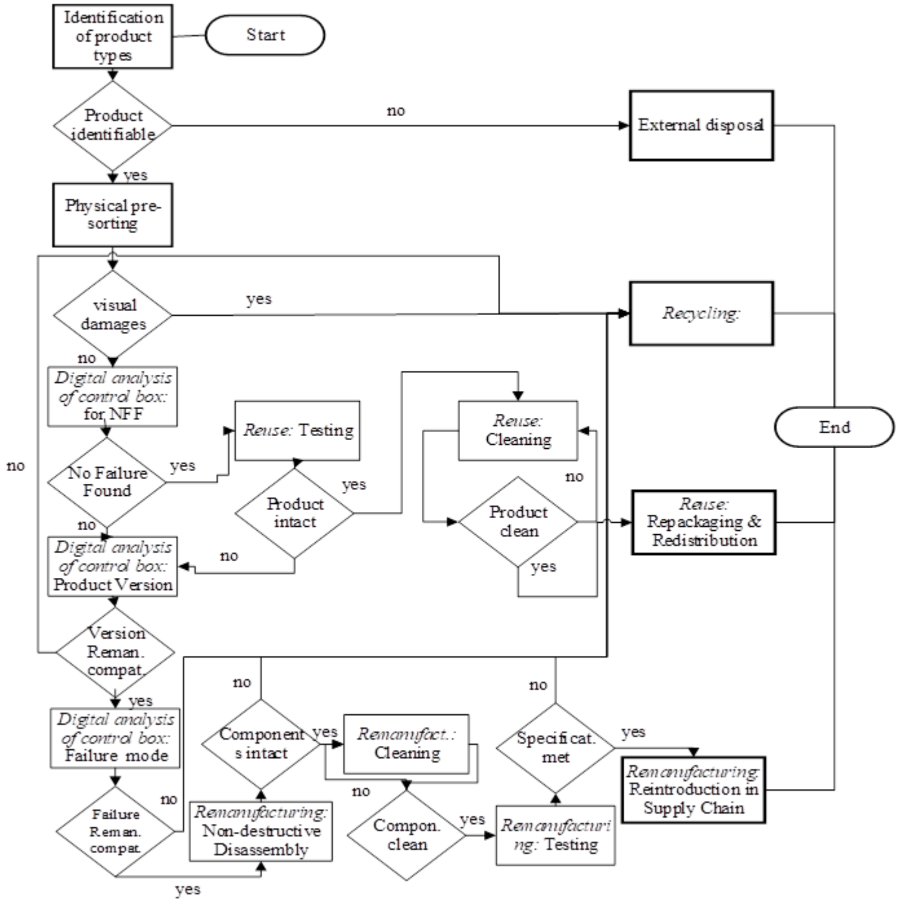

Figure 4-9 Final solution design (3R-Process)

The technical process shown in figure 4-9 was applied in the case study described in Grundfos. Since the illustration is rather complicated due to the iterative testing and cleaning steps, the author has removed the iterative elements in a simplified illustration. As extensively described in paper number 5, each of the empirically investigated resource loops requires a specific set of product data that must be available in order to be executed. In the following, three different types of data are used:

1. data readable by humans: structured or unstructured data that can be acquired by the human organism through sensory perception (e.g., reading a written text; visual evaluation of product condition).

2. data readable by machines (physically present): Structured data that can be captured by machines (e.g., reading a storage medium) (Wickham, 2014).

3. online data readable by machines (remotely): Structured data, supported by concepts such as IoT and big data analysis in real-time or close to real-time via the Internet, which are then externally interpreted.

To be able to recycle a product, at least the material composition and the general product application must be known. To be able to assign the raw materials to the correct recycling stream and to exclude the possibility that the product has been operating in a hazardous environment (e.g., water vs. oil), which would pose a potential hazard to workers in the disassembly line. This data can be obtained from the physical product by humans reading the product identification (ID) number. In order to successfully remanufacture a product, the exact product version must be specified, since even within one product line, multiple small engineering changes can be carried out throughout the product lifecycle, which potentially influences the remanufacturability. Furthermore, it is crucial to know the exact failure mode, as this can also influence remanufacturability (e.g., dry-run of a pump would damage the ceramic bearing, which is hard to identify from visual inspection). The exact version can be determined via the product ID and is, therefore, based on the physical product data readable by humans. The failure mode, on the other hand, can be detected by reading the product control box and is therefore based on electronic data readable by machines. To realize the reuse of a product, data about how the product has performed in the market, failure mode data, and data about how much the product has been used are necessary. This data is only available electronically by reading the control box (failure-, operations log). Figure 4-10, one can see a simplified process in which data requirements for each resource loop are highlighted.

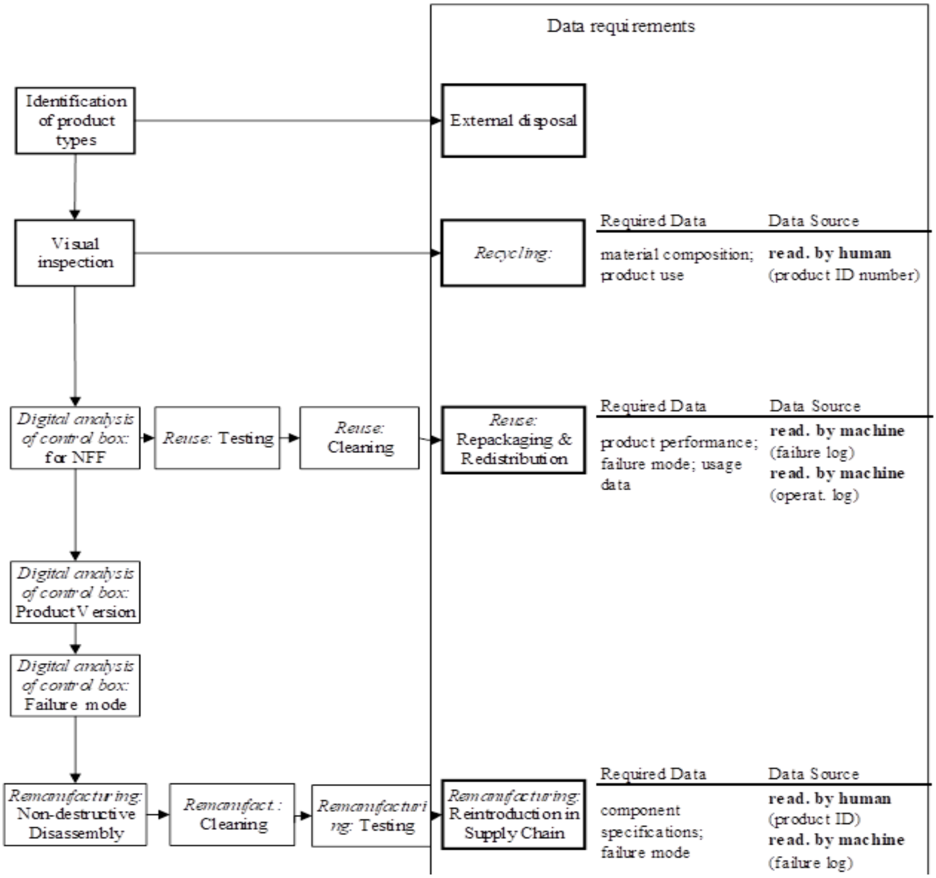

Figure 4-10 Simplified solution proposal inc. data requirements

As described in the introduction, Grundfos is currently in a brownfield environment. Products that need to be taken back from the market are not optimized for take-back and recovery loops.

However, to add value to new product development from this study, the author asked the project team to look beyond the available case and identify what data needs to be available to reach the next narrow resource loop. This is maintained/ prolong product life. This could be done by using more durable materials, but Grundfos is already at the technical limit of wear and tear reduction and this would lead to a significant increase in standard unit costs, which is not acceptable in a conventional business model. The result of the final workshop showed that in order to achieve the maintain/prolong product life resource loop, live performance data and a real-time analysis of this data is necessary. The concept used here has extensively been discussed in the literature under the umbrella of predictive maintenance. By equipping a device with sensor technology, connecting it to the Internet, and live performance analysis, devices can be replaced or repaired before irreversible damage occurs (MacArthur, 2016). This strategy is based on a live data link between the product in the market and the case company. It uses predictive analytics, an analysis method that makes predictions for the future based on big data (Krüger et al. 2017, 103; Hoppenstedt et al. 2017). In concrete terms, predictive maintenance uses the latest measuring techniques to collect large amounts of data on the products and components to be monitored, enabling demand-oriented forecasts of the maintenance work to be made without delay as a direct response (Eckert 2017). Necessary maintenance measures can, thus, be well planned and scheduled in such a way that the product performance is impaired as little as possible (Scheffer & Girdhar 2004). The measurement of critical parameters such as temperature or vibration can provide information about whether and when a drop-in performance or even failure of a product may occur. Both diagnostics and forecasting are important to core processes in the application of this maintenance strategy (Peng et al. 2011). This would enable Grundfos to maintain the product before it becomes inoperable. The performance data identified by the project team is the volume of water moved per time, the temperature of the electronics, and the level of vibration. Sensors in the pump already record all these performance indicators, and the latest version is even Wi-Fi capable, but there is no infrastructure to collect and analyze the data yet. Hence, the new resource loop: “*enabling maintain/ prolong product life*” will be added to the final framework, but not be tested in reality due to practical limitations. Following figure 4-11 summarizes the identified data requirements for each resource loop.

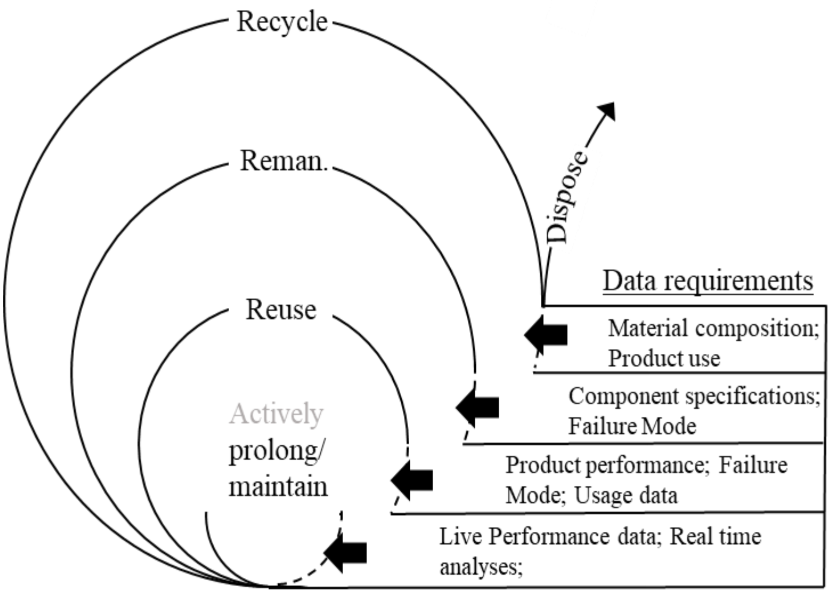

Figure 4-11 Data requirements unlocking different resource loops

4.3.3. EMPIRICAL RESULTS

The 3R process was tested in cooperation with a strategic customer on a sample of 603 warranty pumps. Conventionally those pumps have been recycled for the recovery of raw materials in the past years. To get deeper insights into the case, please refer to paper No. 5. Since the resource loop “actively prolong/ maintain” has not been tested in the pilot setup, the presented results are limited to recycling, remanufacturing, and reuse.

In the following, the author will present the results in terms of both financial and environmental performance. For reasons of discretion, he encoded the financial performance indicator with a non-disclosed factor and chose the artificial unit MU (monetary units). The environmental performance was measured based on LCA (Life Cycle Assessment) data, water consumption and carbon dioxide emissions were chosen as relevant factors. For a detailed description of the calculation, please see the research paper number 5. The reference point for both the financial and environmental evaluation is manual recycling, as this is the current as-is situation in Grundfos.

The author will first compare financial performance. He does this in 3 dimensions: (a) Process Costs, (b) Turnover, and (c) Profit.

(a) Starting with the process costs; Manually recycling entire products results in 82,4 MU of process costs. Remanufacturing two critical components and recycling the remaining components results in 129,5 MU. The process cost for reusing an entire pump is 18,2 MU. One can see that remanufacturing inhibits the highest process costs. As remanufacturing implies compliance with like-new or even higher quality standards, this recovery process usually comprises extensive cleaning and testing steps, which drive up the process costs. Contrary to remanufacturing, reuse does not comply with like-new quality standards, Because the product is only tested for functionality and afterward reused in its entirety, processes such as disassembly are not required, which again results in significantly lower process costs. In the present case, recycling is more expensive than reuse. Here it should be noted that this is due to the manual, largely non-destructive disassembly process applied by Grundfos. Conventional recycling, as it is carried out by specialized waste handlers, is characterized by destructive, highly automated processes, such as shredding melting (EMF, 2013).

(b) Also, turnover shows significant differences; Grundfos manual recycling process results in a financial turnover of 100 MU. Even though Grundfos only remanufactures around 10% of the product and recycles the remaining components, the turnover results in 242.2 MU, which is still significantly higher than full recycling. The strong effect of remanufacturing on the turnover comes due to the large difference between raw material and functional value. This difference reflects even stronger when a product can be reused in its entirety. Reuse creates a turnover of 1.440,0 MU.

(c) Based on the aforementioned costs and turnover, the profit for the three investigated resource loops was calculated. The profit in the current case, where all products despite remaining functional values are recycled, results in a profit of 38,3 MU. Because of the simplified calculations due only account for a fragment of the total business case and ignore any additional auxiliary and overhead costs, the real profit is more likely to be set somewhere around +/- 0. Remanufacturing around 10% of the pump and recycling the remaining components results in a profit of 131,2 MU. Despite the higher process costs, the even more significant turnover results in a significantly better business case. Reusing the entire product results in a profit of 1440,0 MU; this outperforms remanufacturing by a factor of ten and once again proves the importance of recovering functional value.

In figure 4-12, it can be seen a simplified overview of the results just presented.

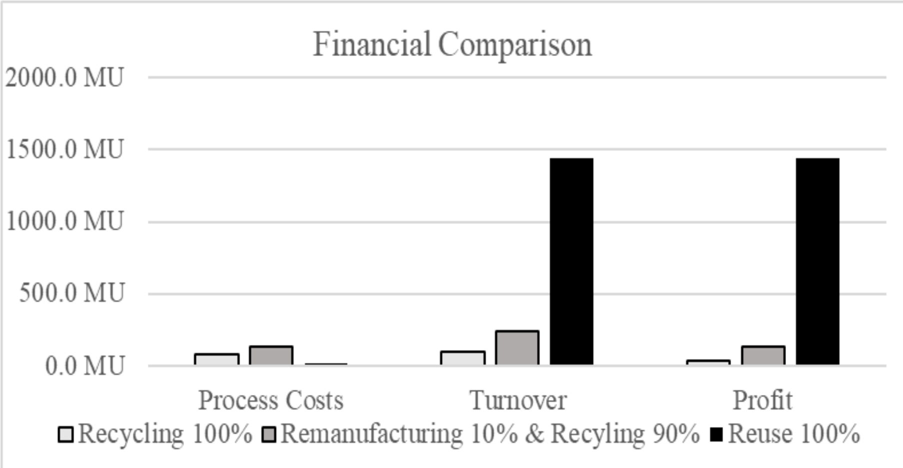

Figure 4-12 Financial comparison

Now the author compares the environmental performance as described above; he chose the dimensions of water consumption and CO2 emissions.

LCA data are used, but only emissions are considered that occur during the mining, manufacturing, and EoL phases. Emissions from the use phase are not included in the calculation. Since the technology of the specified pump type is mature, and no further energy efficiency improvements are expected or planned, the author excluded use-phase emissions as a constant variable from his calculations. The outset and reference point of his calculations is recycling, as this represents the status quo. Hence he is presenting results of the remaining resource loops always relative to recycling, and recycling a complete pump results in an emission of 41,3 kg CO2 equivalent and consumption of 161,0 l of water in the specified lifecycle stages. Remanufacturing around 10% of the product leads to a reduction of around 1,4 kg CO2 equivalent (3,3%) to 39,9 kg CO2 equivalent and 33,6 liters of water (20,8%) to 127,4 liters. Jumping to the next resource loop "reuse" reduces the C02 emission significantly compared to recycling by saving 14,5 kg CO2 equivalent (35,1%) to a total of 26,8 kg CO2 equivalent. The impact of reusing a whole product on water consumption is even more substantial. Compared to recycling, it reduces water consumption from 161 liters to only 8,5 liters by 152,5 liters (94,7%). Figure 4-13 summarizes the discussed environmental implications.

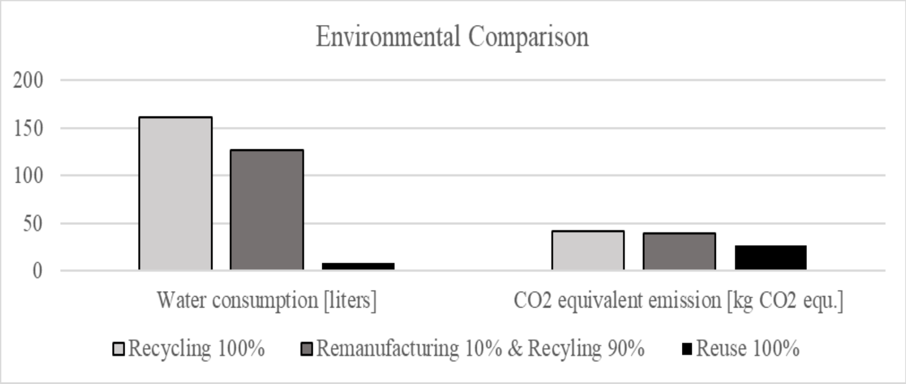

Figure 4-13 Environmental comparison

Now that each resource loop is financially and environmentally quantified, one is also able to quantify the environmental and financial performance of the solution proposal (see *figure 4-12* and *figure 4-13*) applied in the case of 603 warranty pumps. By implementing the solution proposal, Grundfos can move from 100% recycling to 25% reuse of entire pumps; approximately 53,8% were remanufactured (10% of the pump remanufacturing, and the remaining 90% recycled,) and 21,2% entire pumps were recycled. From a financial point of view, implementing the process enabled Grundfos to move from a recycling only profit of 23,094.9 MU into a 3R (reuse, remanufacture, recycle) profit of 262,576.5 MU. In other words, Grundfos was able to multiply the earning by a factor over 11. From an environmental point recycling all 603 products would result in an emission of 24.9 tons of C02 equivalent greenhouse gases and consumption of 97,083 liters of water. The environmental impact after applying the data-driven 3R process results in an emission of only 22.4 tons of C02 and consumption of 64,805.7 liters of water. Whereas the savings in greenhouse gases are 10%, the water savings are even 33.25%.

4.3.4. THEORY DEVELOPMENT

The case study shows that the higher the resource effectiveness, in other words: the tighter the resource loop or; the more functional value is recovered, the better the financial performance of take-back initiatives. This finding confirms the work of previous publications by the Ph.D. candidate and other authors working in the research domain (Bockholt, 2020; Tolio et al., 2017; MacArthur foundation, 2013; Braungart et al., 2007). The environmental performance of the Circular Economy is frequently questioned in the current literature. Popular examples are the authors Allwood (2014) and Andersen (2007), who challenge the environmental benefits of the circular economy. However, it is essential to note that both limit their work to recycling as an EoL value recovery initiative.

From the candidate's research, it becomes clear that if the functional value exists, the potential of the circular economy from an environmental point of view lies in optimizing its preservation. This aligns with the concept of the power of inner circle from the Ellen MacArthur foundation: the closer the product gets to direct reuse, i.e., the perpetuation of its original purpose, the more significant the cost savings will be in terms of material, labor, energy, capital, and the associated externalities. (MacArthur Foundation, 2013). Based on the presented case, the author is able to testify a proportional relationship between the recovery of functional value and the environmental impact of the circular economy. At the same time, his work attests that with increasing functional value, the data required to recover it increases proportionally. The author identified three types of data. The first type is what he refers to as data readable by humans. This data can be structured or unstructured. An example of structured data readable by humans could be reading the product ID number. An example of unstructured data readable by humans could be identifying the product by its appearance. The second type of data is data readable by machines. This type of data is typically structured. It can be extracted by reading out the product's control box (e.g., failure mode, performance data) with the help of an electronic reading device. The third type of data is what the author refers to as online data (Wickham, 2014). He categorizes online data as data that is captured, shared, and analyzed in real-time through technologies within the domain of cyber-physical

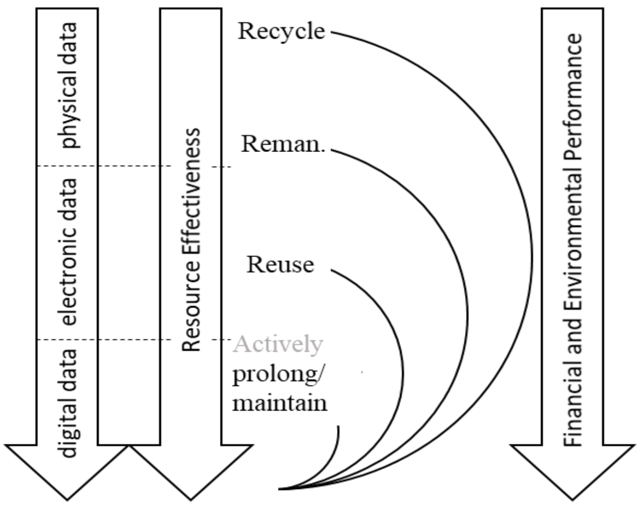

Figure 4-14 Key findings overview

systems. Figure 4-14 visualizes the identified relationship between product data, resource effectiveness, resource loops, and the resulting financial and environmental performance.

Using the analyzed case example, I could show that even in a brownfield application, information can be read and used to increase resource effectiveness and, thus, the financial and environmental performance of take-back initiatives without the need to upgrade to new technology. The bottom-up approach highlights the point at which digital technologies become indispensable to increase resource efficiency further. This is where live data must be transmitted and analyzed to extend the life of the pumps actively.

4.3.5. ADDITIONAL INSIGHTS AND REFLECTIONS

As research paper No.5 is the author´s latest work and is currently in the peer-review process in the Journal for Cleaner Production, it represents the state-of-the-art of his research. For this reason, unlike

WP1 and WP2, there are no additional insights and reflections that could have been collected after the publication of the paper.

4.3.6. THEORETICAL IMPLICATIONS

With the third work package, The Ph.D. candidate contributes to the academic body of literature of circular economy and information technology. As pointed out in the research context of this work package, potentials of digital technologies as enablers for a circular economy are a trending research topic. In contrast, the present state of literature focusses solely on rather incremental efficiency improvements within a defined resource loop. One can see a more radical but also a more robust application of data management and information technologies by utilizing it as a key enabler for resource effectiveness. The Ph.D. candidate is the first author, who empirically proves and describes the role of data as an enabler for different resources loops as well pin-pointing the spot where digital concepts are not a nice to have but are required to unlock a closer resource loop.

4.3.7. PRACTICAL IMPLICATIONS

The practical contribution of this work package can be divided into two parts. The first part is the knowledge contributed to the current state of the industry, the brownfield. Based on the analysis of existing product data, the research enabled Grundfos to develop remanufacturing and reuse as a new resource loop in addition to existing recycling. This has significantly improved the financial and environmental performance of Grundfos' take-back initiative. The second part is the knowledge that contributes to the future development of the industry. The consideration of the findings in new product development enables Grundfos to create a new "greenfield" scenario in which products communicate with Grundfos and thereby significantly extend their life.

CHAPTER 5. CONCLUSION

The following chapter concludes this doctoral thesis. For this purpose, the research contribution is summarized and evaluated against the initial research objective. Also, the limitations of this thesis are presented and discussed. Finally, promising avenues for future research are highlighted.

5.1. RESEARCH CONTRIBUTION

The objective of this doctoral thesis presented in the first chapter was:

To understand transitional challenges and to develop reverse supply chain capabilities for closing resource loops in the discrete manufacturing industry.

The motivation behind this research objective was that reverse supply chains, as opposed to linear, forward-supply chains, contain numerous uncertainties. These uncertainties relate to the location of EoL products in the market, the quantity of returned products, and the quality (e.g., type, version, condition) of these products. A poor understanding of the functions of the reverse supply chain means that they are often not economical and, therefore, rarely a part of the core business of a vast majority discrete manufacturing companies but a separate marginal side activity. A large majority of current research in the field of circular and reverse supply chain management refers to a greenfield scenario in which product (e.g., design for disassembly) and business model design (service-based business model) can be changed. Considering the often-significant life span of discrete manufacturing products, it becomes clear that these greenfield strategies are essential but possibly will first come in full effect in decades (at the end of the product life).

In contrast, there are currently millions upon millions of products on the market that are not designed for several life cycles, neither are they localizable, nor predictable in their return flow and condition. Despite the particular difficulties of the current brownfield situation, the social and legislative pressure on producers is great and increasing. The first directives make European producers of certain discrete manufacturing products responsible for the end-of-life of these products (e.g., the WEEE directive). In addition, an expansion of the legal framework for the promotion of the circular economy is expected.

By not understanding the financial implication of reverse supply chain design for EoL product returns and by not offering strategies, which target specific challenges of the current brownfield transition phase of the industry, literature offers only little guidance into how to transform a business from the current linear state to a circular business successfully. The publications embedded in this dissertation build a bridge between the necessary future scenario of an industry-wide circular economy and its current linear orientation, by putting a particular emphasis on the transitional period. Table 5-1 shows the main contribution of the individual publications and reflects at the same time on their usefulness in industry and the robustness of the research. Even though the developed reverse supply chain capabilities were developed with the discrete manufacturing industry in mind, many reverse supply chain capabilities have a more comprehensive application and also hold up in other industries. This is elaborated in the individual papers in the appendix. The aggregate contribution of this doctoral thesis is greater than the sum of the individual contributions of the research papers. The doctoral thesis provides a comprehensive and detailed view of the challenges and solutions concerning specific challenges and opportunities of the current transitional era of the industry towards a circular economy. The challenges and solutions are represented through a series of real cases and applications in industry. A wide field within the research area of reverse supply chains is covered. This can be justified by the fact that the submitted thesis does pioneer work in the field of brownfield supply chain transformation for reverse supply chains.

Other research that has been done in this acute area of supply chain research is virtually non-existent. The breadth of the work allows researchers and managers alike to gain a good overview of the most critical problems and viable solution proposals. Nevertheless, some reverse supply chain relevant topics were deliberately left out. In order to respect the natural limitations of time and human resources, traditional efficiency improvements were mainly left out of consideration. Disassembly and sorting processes, in particular, represent an unprecedented challenge for manufacturers due to the heterogeneity in volume and condition of EoL products. However, the scope of the project focuses on effectiveness (the jump between resource loops), as this is where the more urgent research gap has been identified and where the financial and environmental impact is more significant. Furthermore, this research gap is better addressed by existing literature focusing on the technological solution (e.g., Linstrøm, 2018; Butzer et al., 2016).

Table 5-1 Research contribution

Work package	**Reverse supply chain capability**	**The industrial context in which research findings have been applied**	**Advantages and disadvantages of implementation**	**Robustness of the findings**
WP1	Factors affecting the financial performance of take-back initiatives	Building a Grundfos take-back system in England	Findings help to select suitable markets and customers/ Still dependent on the exceptional commitment of individuals as reverse supply chain operations due not align with local KPI's	The validity of the factors depend on the industrial context
WP2	Search and process strategies for EoL take-back initiatives	Grundfos Resource Recovery project	Mixing active and passive search- and suitable value recovery strategies enables a balanced portfolio	The validity of the factors depend on the industrial context
WP3	Product data as a key enabler for resource effectiveness	Grundfos remanufacturing project	Findings help to unlock the recovery of functional value moving from recycling to remanufacturing and reuse, which boosts the environmental and financial performance of Grundfos take-back	Only tested on small sample Based on a single case

In addition to the academic contribution of this dissertation, which took the form of presentations at international conferences and publications in peer-reviewed journals, other forms of knowledge dissemination took place. This took place through intra-company presentations of the Ph.D. candidate, for example, at Grundfos materials day 2019 or Grundfos Technology push event 2019. On the other hand, knowledge dissemination also took place within university circles within the framework of the Industrial Sustainability Circle at Aalborg University or the sustainability research group at the University of Cambridge in England. Besides, there were also events with larger audiences, such as the Otto Mønsted award ceremony 2019, where the research of this thesis was awarded and presented to an audience of over 1000 participants from various industries.

5.2. LIMITATIONS

As with any research, this thesis is also subject to many limitations. Challenges and solutions were tested exclusively within Grundfos A/S. Although this was done in numerous different cases of different business units, some context variables influence Grundfos cases across the entire organization, such as the private foundation-based ownership structure, which allows Grundfos to pursue long-term goals even if they reduce short- mid-term profit. To reduce context bias, identified challenges and solutions have been abstracted to universal characteristics so that they can be applied to reverse supply chains (EoL take-back initiatives) in the discrete manufacturing industry. Examples for these characteristics are the highly fluctuating quality of the returning EoL products, different internal and external origins, high fluctuation of the return volume flow, and the complex supply chain with different stakeholders within and outside the company. Another significant limitation is the role of the researcher. Within the industrial Ph.D. program, the researcher was part of Grundfos A/S's staff through a permanent employment contract. In this context, he took over project management responsibilities (e.g., EoL take-back UK, resource recovery). Being a part of the Grundfos Circular Economy team, he was integrated into the daily business processes. This can potentially lead to an insider-bias, which hinders the researcher from noticing problems and conflicts associated with the developed solutions. Besides, there are, of course, conflicts of interest between research and industry. The explorative nature of it cases do not always depend on academically neutral, generalized selection criteria, but is often determined by random factors occurring in practice (e.g., extraordinary commitment to the sustainability of highly ranked stakeholders). Another significant limitation is the evaluation of the different solutions that have been developed within the scope of this research.

In many cases, this evaluation was carried out by the industrial team to which the researcher himself belongs, which can lead to insider-bias. Financial indicators such as business cases have often been calculated pragmatically without considering all costs in detail (e.g., indirect costs). To learn more about the limitations of the individual papers, please refer to the several papers in the appendix.

5.3. FUTURE RESEARCH

As can be seen from Table 5-1, future research should, above all strengthen the robustness of the results presented here. Two different kinds of work can do this. On the one hand, new reverse supply chain challenges can be identified, and solutions can be added to those presented, and on the other hand, existing solutions can be improved. Across all topics discussed in the work packages presented in section four, the Ph.D. candidate sees the general trend that today's research plays mainly in a long-term future scenario and short-midterm challenges in the industrial transition to the circular economy are largely ignored. This is an evident and urgent research gap. Furthermore, research in the field of reverse supply chain design, strategy, or enabling technologies always seems to be strongly influenced by the efficiency dogma of supply chain research from the last decades. Based on the findings of this thesis, more fundamental research focusing on the effectiveness of value recovery is needed to ensure a successful circular transition.

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APPENDICES

Appendix A. Paper I

Bockholt, M.T., Kristensen, J.H., Colli, M., Jensen, P.M. and Wæhrens, B.V., 2020. Exploring factors affecting the financial performance of end-of-life take-back program in a discrete manufacturing context. *Journal of Cleaner Production*, p.120916.

Appendix B. Paper Ⅱ

Bockholt, M.T, Jensen, P.M. and Wæhrens, B.V., 2017. A historical case study on Circular Economy. Presented at the EurOMA sustainability forum in Kassel, Germany.

Appendix C. Paper Ⅲ

Bockholt, M.T., Kristensen, J.H., Wæhrens, B.V. and Evans, S., 2019, December. Learning from the Nature: Enabling the Transition Towards Circular Economy Through Biomimicry. In *2019 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)* (pp. 870-875). IEEE

Appendix D. Paper Ⅳ

Bockholt, M.T., Kristensen, J.H., Jensen, P.M Wæhrens, B.V. and Evans, S., 2020 The foraging company: Mimicking biosphere strategies to empower Circular Economy. submitted for a first round of review at the Journal of Industrial Ecology.

Appendix E. Paper Ⅴ

Bockholt, M.T., Schwarz, K., Chaudhuri A., Jensen, P.M and Wæhrens, B.V. 2020, Realizing the Financial and Environmental Potentials of End-of-Life Take-Back Initiatives: A Design Science based investigation. submitted for a first round of review at the Journal of Cleaner Production. An earlier version of the paper is presented at the 4th EurOMA sustainability forum in Cernobbio, Italy.

Appendix F. Idea Award

Based on the results that I developed during my academic exchange terms at the Institute for Manufacturing at the University of Cambridge, I decided to create a Circular Economy Consulting Principle together with my colleagues and friends Michele Colli and Jesper Hemdrup Kristensen. The idea was to teach industrial organizations different search and process strategies for End-of-Life products, which are based on foraging strategies of predators in nature. In September 2019 our work was awarded the second prize of the Otto Mønsted bright Idea Award, which was endowed with 100.000 Danish Kroner.

> "*Otto Mønsted's The Bright Idea is a recognition of talented students, researchers and businesspeople, who are developing innovative solutions which show significant development within their given field of study*." (Otto Mønsted Foundation, 2020)

2. Markus Bockholt, Ph.D, Michele Colli, Ph.D., og Jesper Hemdrup Kristensen, postdoc, alle fra Aalborg Universitet – vinder af 100.000 kr.
The Bright Idea: At udvikle en forståelse for genbrugsmønstre i industrielle organisationer, inspireret af modeller for rovdyr og byttedyr i naturen, så virksomheder i højere grad kan opnå en cirkulær produktion.

Begrundelse: "Juryen havde lagt særlig vægt på, at gruppen af forskere har anvendt og valideret deres metode og opnået betydelige resultater i en industriel kontekst."

Otto Mønsted Foundation, 2020, The Bright Idea Award, viewed 28 August 2020, <https://omfonden.dk/application/>

Appendix G. Resource Recovery in Grundfos

Especially motivating were hands-on projects in Grundfos. A special story resulted from a coincidental find of several pallets of red-alert pumps in the scrap yard of Grundfos' German subsidiary.

Global collaboration saves valuable resources

More than 5,000 SQ pumps were meant to be scrapped due to a motor failure. Thanks to Markus Thomas Bockholt and other enthusiastic colleagues' careful considerations and drive, a much more sustainable solution was devised.

03/05/2019 12:45 Bjarke Nystrup Sørensen

What should be done with 5,210 SQ pumps collecting dust in the German production company., CWP? The pumps are unsaleable due to an error in the motors which may cause an electrical short circuit. That is the reason why they have been recalled from wholesalers and sales companies in the EMEA region.

"The easiest solution would be just to scrap them. Sometimes it is easier just to look the other way and let something go to waste. The idea of scrapping would truly hurt, since only one of several hundred components was damaged in each pump," says Joost Maarse, Lead Project Manager, Group EHS.

Reusing components

However, scrapping was not an acceptable solution to the problem for either him, his Group EHS colleague, Markus Thomas Bockholt, or his German colleagues, Ruth Kerschhaggl and Werner Koslowski. They went for a much better solution for the environment as well as for the economy.

"The hydraulic part could be reused one-to-one in new products, if disassembled from the motor, or it could be reused as single components. As for the motors, the permanent magnet rotor and the electronic unit, which are the most expensive parts, could also be reused one-to-one, if the motors were disassembled," says Werner Koslowski, Senior Project Manager, Quality and Sustainability.

Returned to Mexico

No sooner said than done. Colleagues in the German logistic department started identifying the affected pumps after which shop floor workers sorted them by type and removed all cables. Then, the pumps were returned to Mexico, where they were originally produced, and received by colleagues also favouring the idea of reusing components. At the Mexican factory, the pumps were disassembled, so that some of the components could be incorporated in the production of new pumps, and the remaining parts could be sold for recycling.

"What has been done is by far the best solution in terms of the economy as well as the environment, even if it was not easy. It is all based on good colleagues' commitment and responsibility," says Joost Maarse.

The amount saved by the initiative totals almost 1.8 million DKK. If the pumps had been scrapped, the recycling value would only be 75,000 DKK.

Joost Maarse hopes that recycling valuable resources will be common practice someday, and he invites everybody to contact Group EHS if they experience situations similar to the one in Germany.

SUMMARY

Our current economic system is fundamentally ill-structured. Its linear layout, which works under the take-make-waste premise, ignores the natural limits of planet earth, which makes its failure in the long run inevitable. 250 years after the first industrial revolution, human society sees itself confronted with consequences such as environmental pollution, global warming and critical resource depletion. There is academic and political consensus that a transformation to a sustainable, circular economy is an imperative. Circular Economy is a sustainable development initiative, aiming to eliminate the negative impact of human production and consumption on the environment. It aims at keeping raw materials, components and products in a cycle, following the example of nature. This is achieved by changing from linear material and energy flows to materials cycles and renewable and cascade-type energy flows. First supranational laws have been passed that make discrete manufacturing companies responsible for the products they produce, and ultimately take responsibility for the point at which they reach the EoL (End-of-Life) stage and turn into waste. Over the past decades, the discrete manufacturing industry has produced and sold millions of goods to the consumer market. However, this has happened under the traditional take-make-waste paradigm without considering multiple product life cycles. On the one hand, the conventional, transaction-based business model used here makes it very difficult to locate products at the end of their life cycle and, on the other hand, the absence of life cycle-based product design makes it very difficult to recover sufficient value. This makes EoL products a legacy problem for many producers, since economic exploitation is an unsolved problem. In contrast to the traditional forward supply chain, in which today's research and industry have great expertise, reverse supply chains, their functions and mechanisms are largely unexplored, especially with regard to EoL products.
The present thesis supports the discrete manufacturing industry in the current brown-field transition through its objective:
To understand transitional challenges and to develop reverse supply chain capabilities for closing resource loops in the discrete manufacturing industry
The insights gained in this thesis cover the most important basics needed to build a financially and environmentally sound reverse supply chain in the current transitional phase we are in. The special focus is on the short- midterm transitional phase targeting the prevalent legacy problem.

- Factors impacting the financial profitability of current EoL take-back initiative
- Supply chain strategies for the search of EoL products
- Supply chain strategies for the recovery of value from EoL products
- Maximization of resource effectiveness through utilizing product data

The solutions presented include structural supply chain elements, such as factors to be considered when designing reverse supply chains as well as supply chain strategies for the search and recovery of EoL product value. This dissertation contributes to literature in twofold ways. Firstly, contributing to existing literature on reverse supply chains with design element especially relevant for returning EoL products. Secondly, as a pioneer in classifying search and value recovery strategies enabling a structured transition in the current brownfield scenario

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